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Increasing Energy Efficiency and Reducing Emissions from China's Cement Kilns: Audit Report of Two Cement Plants in Shandong Province, China

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July 2011

This work was supported by the U.S. Environmental Protection Agency, Office of International Affairs through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Abstract

The study documented in this report was initiated in order to conduct an energy assessment and to identify the relationship between combustion issues and emissions from cement kilns. A new suspension preheater/precalciner (NSP) rotary cement kiln at one cement manufacturing facility (referred to as Shui Ni 1 in this report) and a vertical shaft kiln (VSK) at another cement manufacturing facility (referred to as Shui Ni 2 in this report), which are both in Shandong Province, were selected to conduct the energy and emission assessments through collection of data. Based on analysis of the data collected during this assessment, several actions are suggested that could lead to reduction in coal use and reduction in emission of gaseous pollutants from the system.

Specific actions suggested for NSP rotary kiln at Shui Ni 1 Cement Plant are: 1. reduce excess air use in coal burners, 2. reduce air leakage in the system through control of pressure and/or eliminating openings or gaps through which air leaks into the system, and 3. use of improved insulation and refractory in the kiln. These measures, if fully implemented, would reduce net (actual use minus equivalent of power production) coal consumption from 119 kg/ton kg of clinker to 103 kg/ton of clinker or a reduction of 16 kg coal per ton of clinker production – a reduction of 13.4%. Using a coal cost of 400 RMB/ton of coal, 360 days/year operation, and 5000 tons/day (approximately 208 tons/hour) clinker production rate, potential savings would be 11.52 million RMB/year.

Specific actions suggested for VSK at Shui Ni 2 Cement Plant are: 1. Preheat nodules by using hot water and/or using waste heat. 2. Pre dry nodules using waste heat from exhaust gases or air used for cooling nodules. 3. Reburn CO-combustible gases and recover heat for use in the process or plant. 4. Reduce areas of air leaks to increase temperature of exhaust gas and use a heat exchanger to recover heat by recovering heat for nodule making process. 5. Control kiln pressure to avoid negative pressure at the clinker discharge level.

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1. Introduction

The cement industry is a major source of multiple air toxics, among them persistent organic pollutants (POPs) as well as other emissions such as mercury, carbon monoxide, particulate matter, and greenhouse gases. China is the world's largest producer of cement, manufacturing this essential building material in a variety of kiln types ranging from outdated, inefficient facilities to modern, state-of-the-art facilities.

In 2003, the U.S. Environmental Protection Agency (EPA) and China signed a Memorandum of Understanding (MOU) to cooperate in the areas of clean air, clean water, and toxics reduction. In 2004, the Stockholm Convention on Persistent Organic Pollutants entered into force. The Stockholm Convention is a global treaty that aims to "protect human health and the environment from chemicals that remain intact in the environment for long periods, become widely distributed geographically, accumulate in the fatty tissue of humans and wildlife, and have adverse effects including certain cancers, birth defects, dysfunctional immune and reproductive systems, greater susceptibility to disease and even diminished intelligence" (UNEP, 2008). The Stockholm Convention requires participating parties to "take measures to eliminate or reduce the release of POPs into the environment" (UNEP, 2008). China and the U.S. are signatories to the Stockholm Convention.

In 2004, the U.S. EPA and China's State Environmental Protection Administration (SEPA) [1] developed a plan of work on POPS and other toxics. Under this work plan, the U.S. EPA assisted China under the Stockholm Conversion to inventory unintentional releases of dioxins and furans (Dx/Fu) from combustion sources (Annex C), which includes cement kilns, develop China's National Implementation Plan (NIP) to address dioxins and furans, and implement China's National Implementation Plan for reducing dioxin and furan emissions from cement production.

[1] Now the Ministry of Environmental Protection (MEP).

In 2005, the Foreign Economic Cooperation Office (FECO) of SEPA and the U.S. EPA launched a cooperation project in reducing persistent organic pollutants (POPs) and other toxic pollutants generated from cement kilns. This work was undertaken as part of the framework for scientific and technical cooperation on pollution from POPs and other toxic pollutants, Annex 3 to the framework agreement on Memorandum of Understanding (MOU) between US EPA and SEPA on scientific and technical cooperation on environmental issues. The goal of the project is to decrease emission of by-products such as POPs and other toxic pollutants from cement production and to explore best available technologies/best environmental practices (BAT/BEP) to accelerate the Chinese cement industry's commitment to the Stockholm Convention.

SEPA's Stockholm Convention Implementation Office, in collaboration with the U.S. EPA, conducted several studies and tests during December 2006 to develop emission factors for polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs), and hexachlorobenzene (HCB) in order to estimate the level of unintentionally-produced emissions of persistent organic pollutants (POPs) from the Chinese cement industry. These data indicated the presence of high levels of POPs and other emissions from the tested facilities. Many of these emissions were suspected to be a result of poor combustion conditions in vertical shaft kilns (VSKs) using coal. The study documented in this report was initiated in order to conduct an energy assessment and to identify the relationship between combustion issues and emissions from cement kilns.

A rotary cement kiln at one cement manufacturing facility (referred to as Shui Ni 1 in this report) and a vertical shaft kiln at another cement manufacturing facility (referred to as Shui Ni 2 in this report), which are both in Shandong Province, were selected to conduct the energy and emission assessments through collection of data to identify energy use patterns and possible solutions to reduce energy use as well as associated emissions.

A team consisting of personnel from SEPA, US EPA, Lawrence Berkeley National Laboratory (LBNL), a US-based consultant E3M, Inc., and the China Building Materials Academy (CBMA) visited and conducted an energy assessment at the Shui Ni 1 and Shui Ni 2 cement plants in Shandong Province in September 2007.[2]

Based on the plant visits, CBMA prepared a report on the energy and emissions data measured as well as the energy and mass balance for each of two plants visited, separately (CBMA, 2007a; CBMA, 2007b). The data in these two reports were used by E3M, Inc. along with additional data collected by E3M, Inc. during the site visits, to conduct further analysis on energy efficiency and emission of the plants.

This report begins with background information on the cement production process and related emissions. The report then provides information on cement production in China, describing the predominant types of kilns used. The report then presents consolidated results from the E3M, Inc. analyses of Shui Ni 1 and Shui Ni 2. Overall project results are presented in the final section.

[2] These are pseudonyms. The actual cement plant names are not used in this report.

2. Cement Production

2.1 Process Description and Emissions

Cement is made by combining clinker, a mixture of limestone and other raw materials that have been pyro-processed in the cement kiln, with gypsum. The cement production process requires thermal energy (heat) for production of clinker, which is the primary ingredient for the manufacture of cement. Clinker production typically occurs in kilns heated to about 1450°C. Clinker production is the most energy-intensive process in cement manufacturing.

Heat for cement production is supplied by using coal as a primary source of energy. Coal combustion requires a large amount of combustion air that is eventually released as combustion products or exhaust gases. The cooling air used for clinker cooling mixed with combustion products is discharged as exhaust air or exhaust gases from the plant. These gases include combustion products such as carbon dioxide (CO_2), carbon monoxide (CO), water vapor (H_2O) etc., and CO_2 released from the calcining process itself. In addition to CO_2, CO, H_2O, they also include small but detectable amounts of heavy metal elements that initially existed in the raw materials in vapor form. The presence of these vapors and products of incomplete combustion of coal (CO, hydrocarbons etc.) can result in the formation POPs.

Coal is the primary fuel burned in cement kilns, but petroleum coke, natural gas, and oil are also consumed. Waste fuels, such as hazardous wastes from industrial or commercial painting operations (spent solvents, paint solids), metal cleaning fluids (solvent based mixtures, metal working and machining lubricants, coolants, cutting fluids), electronic industry solvents, as well as tires, are often used as fuels in cement kilns as a replacement for more traditional fossil fuels (Gabbard and Gossman, 1990).

Cement kilns destroy dioxins in the hazardous waste fuels during the clinker combustion process, but dioxins can be formed after combustion if the offgases are not sufficiently cooled. Regulations aimed at reducing fine particulate emissions require that these exhaust gases pass through air pollution control devices (APCDs) such as electrostatic precipitators (ESPs) or fabric filtration (FF) baghouses in order to remove the cement kiln dust (CDK). In order to prevent the formation of dioxins and furans in the exhaust scrubbing systems in wet kilns, the exhaust gases must be cooled below 200°C (UNEP, 2001).

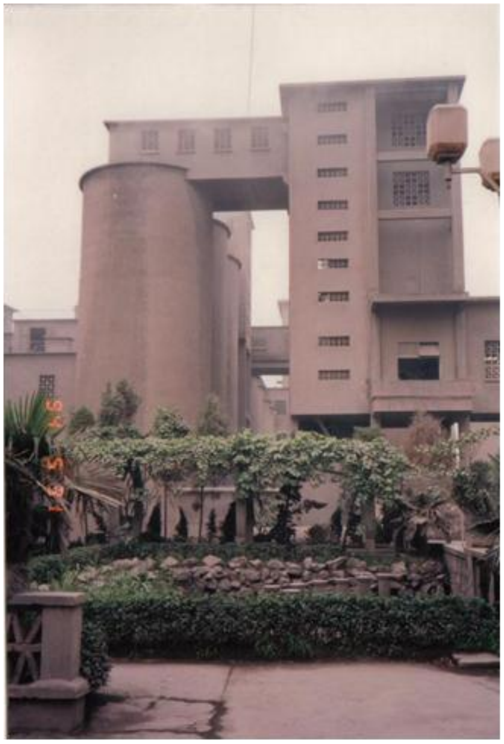
2.2 Cement Production in China

China is the world's largest producer of cement. In 2007, China produced 1,350 million tons of cement, which was 48% of global cement production that year (USGS, 2009).

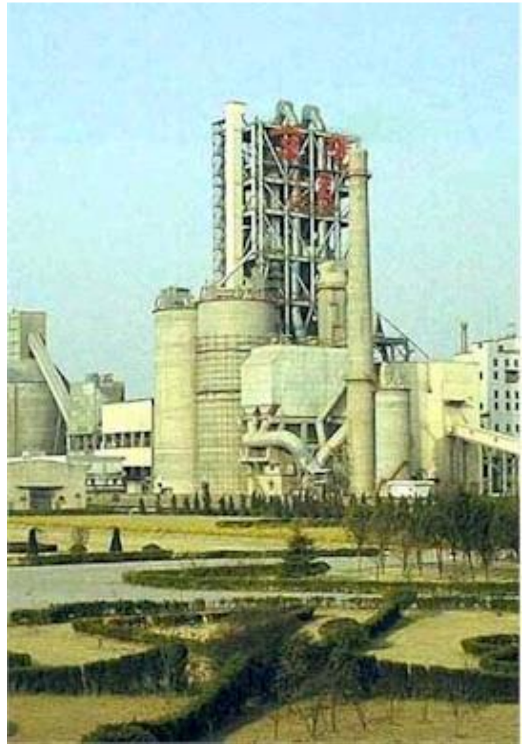
There are basically two types of cement kilns used for the production of clinker in China: vertical (or shaft) kilns and rotary kilns. Figure 1 provides an example of a Chinese kiln of each type. A shaft kiln essentially consists of a large drum set vertically with a packed mixture of raw material and fuel traveling down through it under gravity.[3] A rotary kiln consists of a longer and wider drum oriented horizontally and slight incline on bearings, with raw material entering at the higher end and traveling as the kiln rotates towards the lower end, where burning fuel is blown into the kiln. Shaft kilns, while common in China, are generally not used in the rest of the world to manufacture cement, but the technology has a number of advantages that suit it to local conditions, and intensive domestic research and development have improved the technology considerably since the 1970s. Parallel evolution of shaft kiln technology with the more complex dry process rotary kilns has helped keep the mix of pyroprocessing technologies in China's cement industry more diverse than in almost any other country. The unit sizes of shaft kilns are much smaller than those of rotary kilns, making the former attractive given the system of distributed production that has been encouraged by the transportation system and by political, economic, and other factors. Moreover, construction time for a shaft kiln is one year or less, so it can come on line much faster than a large rotary kiln, which takes two to three years to build.

Rotary kilns can be either wet process or dry process kilns. Wet process rotary kilns are more energy-intensive and have been rapidly phased out over the past few decades in almost all industrialized countries except the U.S. Energy-efficient dry process rotary kilns can be equipped with grate or suspension preheaters to heat the raw materials using kiln exhaust gases prior to their entry into the kiln. In addition, the most efficient dry process rotary kilns use precalciners to calcine the raw materials after they have passed through the preheater but before they enter the rotary kiln (WBCSD, 2004). Figure 2 provides a schematic illustration of a dry process preheater/precalciner kiln (Ash Grove Cement, n.d.).

[3] Shaft kilns are refractory lined tubes, typically 2 to 3 meters in diameter and 7 to 10 meters in height. Most commonly the kilns are made of steel, lined with specially manufactured refractory materials, and housed in buildings 20 to 30 meters in height. The most common capacities are 150 tons per day (tpd) and 300 tpd, roughly equivalent to 50 thousand tons per year (ktpy) and 100 ktpy under normal operating conditions. Shaft kilns require that the kiln be entirely filled with a mixture of raw materials and fuel, with air entering the bottom of the kilns and exhaust gases exiting at the top. The raw material goes through the various pyroprocessing stages as it travels from the top of the kiln to the outlet at the bottom. Preheating and calcination typically occur in the top 15% of the height of the kiln. Clinkering occurs in another relatively small layer. The remainder of the kiln is devoted to a cooling zone. Since air is blown up through the bottom of the kiln nearly all the heat from the cooling clinker is used to preheat combustion air. Shaft kilns require constant attention from operators on a platform at the top of the kiln, who monitor burning conditions, control the rate of kiln feed, open and close vent doors, and manipulate the burning material at the kiln surface with long steel poles.



Vertical Shaft Kiln



Rotary Kiln

Figure 1. Typical Chinese Vertical Shaft Kiln and Rotary Kiln.

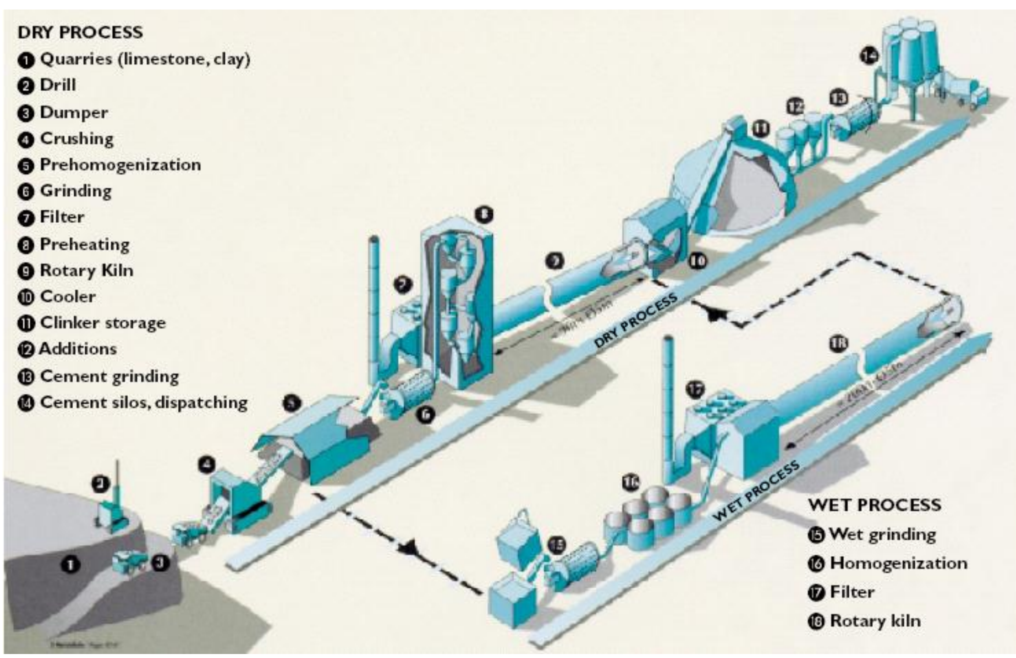


Figure 2. Schematic of the Dry and Wet Cement Manufacturing Processes.

Source: Cembureau, 1997.

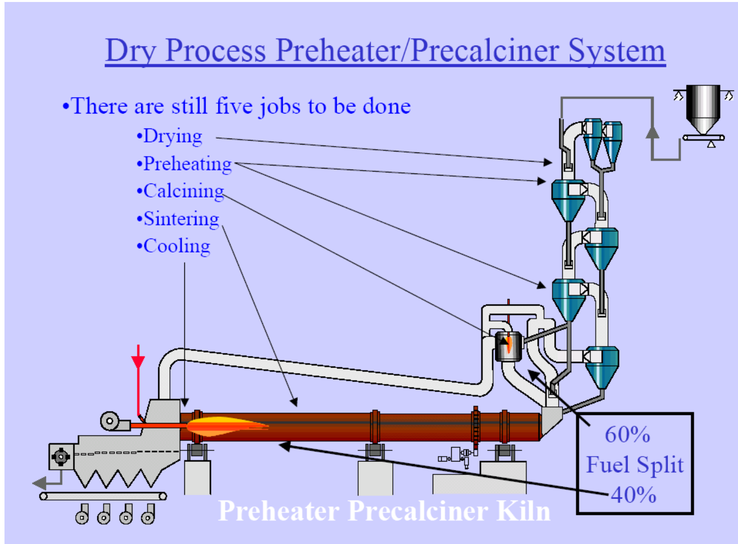


Figure 3. Schematic of a Dry Process Preheater/Precalciner System.

Source: Ash Grove Cement, n.d.

3. Energy and Emissions Assessment for a Rotary Kiln at Shui Ni 1 Cement Plant[4]

The Shui Ni 1 cement plant is owned by a mining group which is a state-owned enterprise. The plant is designed to be comprised of two manufacturing lines, each with clinker production of 5000 tons per day (tpd) and annual cement capacity of 1.5 million tons. The first manufacturing line was completed in 2005. It uses an advanced dry process rotary kiln with a 5 stage cyclone preheater precalciner. It is equipped with an electrostatic precipitator (ESP).

3.1 Process and Equipment Description

The Shui Ni 1 cement plant uses an advanced process that includes equipment for mixing, drying, preheating, precalcining, calcining, and cooling the material to produce clinker. In addition to this, it also uses heat recovery systems such as a cogeneration plant and the heated air to recover a large percentage of the total energy contained in the exhaust gases. An overview of the processes and a simplified view of the material flow distribution with major subsystems or equipment are given in Figure 4.

The raw material consisting of limestone, gangue and other components with approximately 7% to 8% moisture is dried in a dryer that uses heat from boiler exhaust gases to reduce the raw meal moisture content to about 0.25%. The dry raw meal is preheated in five preheaters before being loaded into a precalciner. Preheating is done by using hot gases from the precalciner and the rotary kiln as well as hot air from the clinker cooler. The precalciner uses combustion of coal and gases from the kiln to supply the necessary heat to the material before it is discharged in the rotary kiln for completing the calcining and subsequent clinker burning process. The rotary kiln uses a coal burner and preheated air obtained from clinker cooler. Clinker formed in the kiln is discharged in a grate type cooler where ambient air is used in several stages to cool the clinker and recover its heat for use in several areas of the process and elsewhere in the plant.

Heated air from the clinker cooler is used as combustion air for the coal burners in the kiln as well as the precalciner. It is also used for drying coal in heat recovery boilers to raise steam, and for hot water used in the plant. Eventually this air is discharged as exhaust and ends up going through an electrostatic precipitator to remove its dust content.

The plant has installed a cogeneration system that uses steam and turbine generators to produce up to 6 MW power. The boilers use the heat of exhaust gases from the preheaters mixed with air from the clinker cooler. The exhaust gases include combustion products from the kiln and precalciner and CO_2 generated during the calcining process. Heat from the exhaust gases and mixed hot air are used to generate approximately 22 tons/hour steam at 250 ^{o}C and 0.96 MPa pressure. Boiler exhaust gases are at or above 200 ^{o}C. These gases are taken to a dryer where moisture from the raw meal is removed. In

[4] This section is excerpted from the report prepared by Arvind Thekdi, E3M, Inc.

this dryer, raw meal moisture is reduced from a nominal value of 7% to 8% inlet moisture to about 0.25% moisture while raw meal temperature is increased to about 45 ^oC.

Exhaust gases from the dryer are maintained at about 100 ^oC either by adequate heat transfer in the dryer and/or by injecting water in the gases. This is required to protect performance of the precipitator. With this degree of heat recovery, exhaust gases include flue products from coal combustion, CO_2 generated in the calcining process, some of the moisture removed from the raw meal, most of the cooling air from clinker cooler and any air leakage into the system. Even though the gas temperature is fairly low, perhaps as low as it needs to be to avoid acid condensation in the ducts or precipitators, its heat content is fairly large due to the very large volume of exhaust gases.

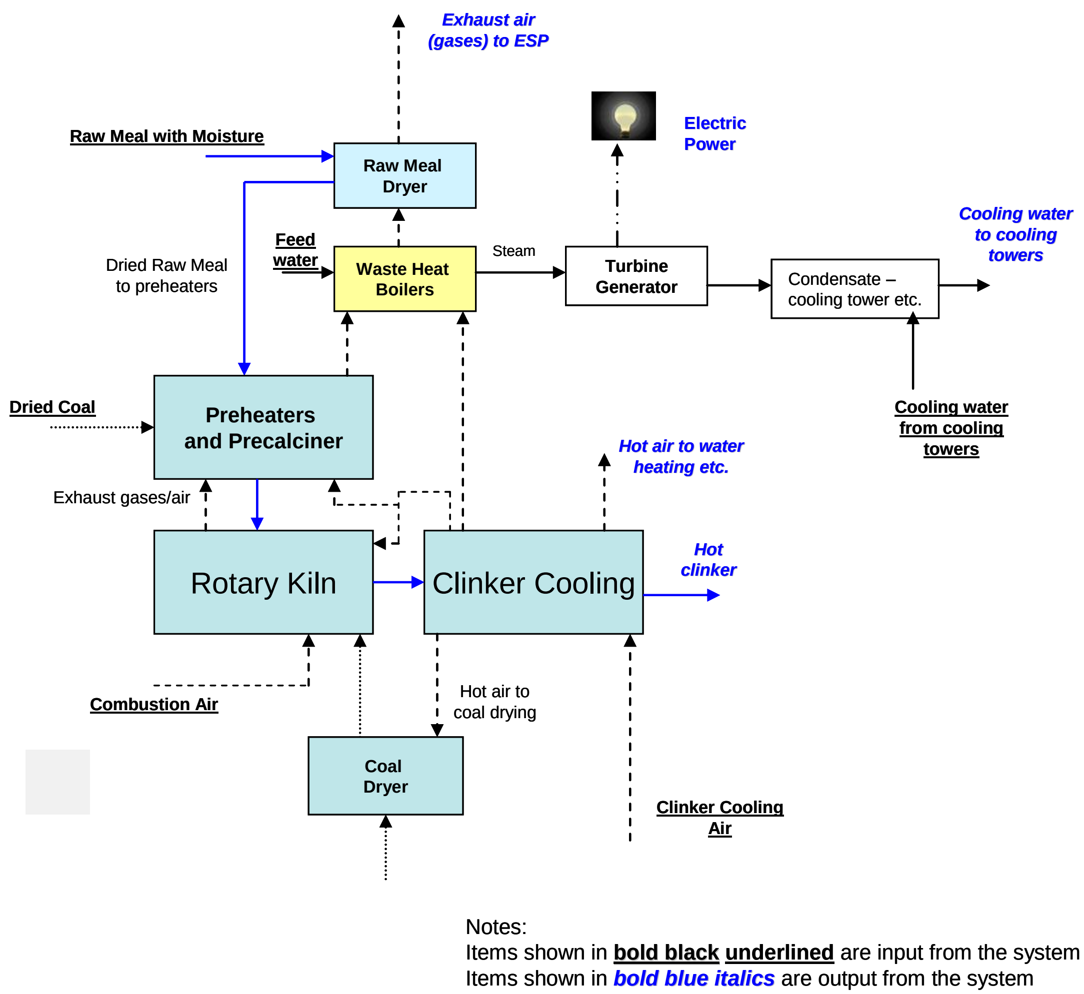


Figure 4. Schematic of the Clinker Production Facility at Shui Ni 1 Cement Plant – China

The CBMA report gives a detail description of the equipment for which data was collected (CBMA, 2007a). A review of the report indicates that much of the heat recovery equipment mentioned above was not covered in the report. Figure 5 shows the equipment for which data are reported and discussed in CBMA (2007a). E3M, Inc.'s report extended the calculations to cover the performance of all equipment and has reported the results based on the revised calculations.

An analysis of the heat recovery equipment and the areas of heat losses from the entire system have been carried out. This approach allows one to consider areas of heat losses and make recommendations to further recover or reduce wasted energy.

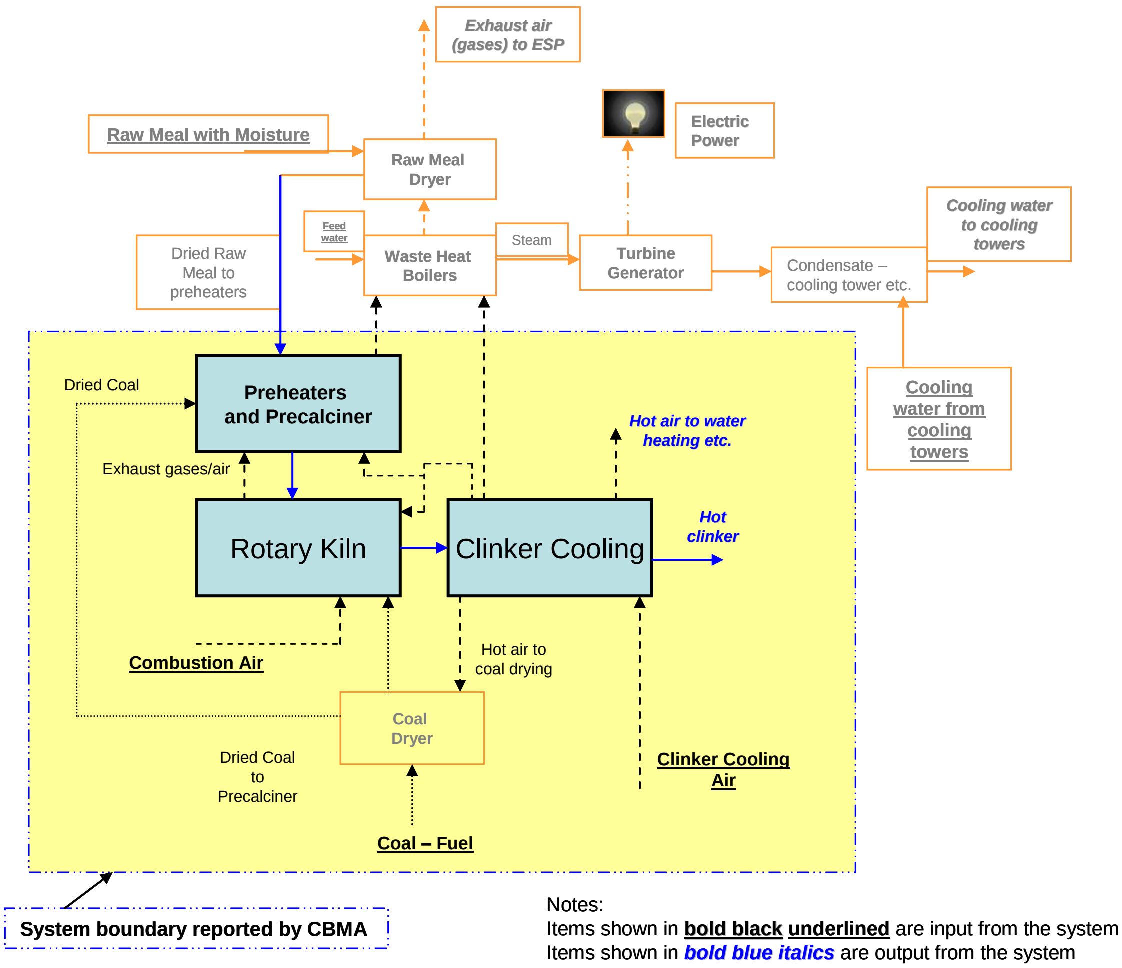


Figure 5. Shui Ni 1 System Boundary as Reported by CBMA

3.2 Measurements and Estimate of Energy Distribution

The CBMA report includes values of several key parameters that allow development of a heat and material balance for the kiln (CBMA; 2007a). A summary of the data collected by the CBMA team is shown in Table 1. The data were used to make additional calculations to estimate energy savings already achieved with use of heat recovery equipment as well as the cogeneration system. The data were also used as inputs for a software program, Process Heating Assessment and Survey Tool (PHAST) developed by the U.S. Department of Energy (DOE).

Table 1. Summary of Data Collected by the CBMA Team (CBMA 2007a)

No.	Position	t_g	t_m	P	C_i	α	G_m	G_g
1	Raw meal fed in kiln	√					√	
2	Outlet of the preheater	√		√	√	√		√
3	Air duct to coal mill	√		√				√
4	Air duct to co-generator	√		√				√
5	Rest air from the cooler	√		√				√
6	Primary air	√		√				√
7	Air for the cooler	√		√				√
8	Outlet of the cooler		√					
9	The surface temperature of whole kiln system							
10	The chemical composition, fineness, moisture content of raw meal							
11	The chemical composition of clinker, f-CaO							
12	The proximate analysis, fineness, moisture content of coal							
13	Coal used in kiln		√				√	
14	Coal used in precalciner		√				√	
15	Air used for coal feeding	√		√				√
Among: P – pressure t_g – gas temperature t_m – material temperature C_i – dust content G_g – gas composition Loss – loss of ignition G_m – the amount of material α – excess air coefficient								

A summary of heat supply and use reported in CBMA (2007a) is given in Table 2. It can be noted that heat from the following streams is recovered in heat recovery systems or the heat is recycled in the system.

- Heat of air exited from the preheater –used for the boiler and then the raw mill dryer
- Heat of air going to coal mill –used for carrying coal into the kiln and precalciner (hence it is recycled back into the system)
- Heat of air from cooler to cogeneration system –used to make steam and power

Certain critical data such as the temperature of kiln surfaces, details of coal gangue composition and amount, pressure in the system that allows infiltration of air, gas analysis at the exit of the kiln, distribution of coal going to the kiln vs. precalciner etc. are not provided in CBMA (2007a). Thus, these values are estimated using calculations and sometimes by assumption. In such cases, values are cross-checked to assure their accuracy.

Table 2. Heat Received and Disbursed (CBMA 2007a)

Heat received					
No.	Sy.	Item	kJ/kg	Kcal/kg	%
1	Q_{rR}	Fuel combustion	3210.2938	767.719	88.28
2	Q_r	Sensible heat of fuel	7.5553	1.8068	0.21
3	Q_S	Sensible heat of raw meal	65.1359	15.5768	1.79
4	Q_{lk}	Sensible heat of primary air	1.5476	0.3701	0.04
5	Q_{yk}	Sensible heat of air for coal feed in kiln	0.5879	0.1406	0.02
6	Q_{lf}	Sensible heat of air for coal feed in precalciner	0.9455	0.2261	0.03
7	Q_{Lk}	Sensible heat of air to cooler	73.1015	17.4817	2.01
8	Q_{Lok}	Sensible heat of leaky air	14.8225	3.5447	0.41
9	Q_{sr}	Heat brought in by gangue	262.4205	62.756	7.22
10	Q_{zs}	Total heat received	3636.4105	869.6218	100

Heat disbursed				
Sy.	Item	kJ/kg	Kcal/kg	%
Q_{sh}	Heat of clinker form	1739.5163	415.993	47.84
Q_{ls}	Heat brought by clinker	157.4866	37.6618	4.33
Q_{ss}	Heat for vaporization of water in raw meal	46.8092	11.1941	1.29
Q_f	Heat brought with air exited from preheater	823.4921	196.9323	22.65
Q_{fh}	Heat brought with dust exited from preheater	30.3969	7.2692	0.84
Q_{Pk}	Heat brought by air from cooler to coal mill	102.7323	24.5677	2.83
Q_{dcf}	Heat brought by air from cooler to cogenerator	428.3572	102.4386	11.78
Q_b	Heat loss from surface	341.9708	81.7799	9.4
Q_{hb}	Incomplete combustion	20.0579	4.7967	0.55
Q_{qt}	Others	-54.4089	-13.0115	-1.5
Q_{zc}	Total heat disbursed	3636.4105	869.6218	100

Additional heat recovery equipment used in the clinker production includes:

- Waste heat boilers that use exhaust gases from preheaters as well as the clinker cooler
- Raw meal dryer section that uses exhaust gases from boilers
- Coal or fuel mill that uses air from clinker cooler
- Turbine generator that uses steam produced in boilers to produce electric power

3.3 Analysis and Recommendations

The discussion regarding improving the system performance is divided into two sections. The first section deals with energy reduction through energy efficiency improvements and the second section addresses reduction of pollutants with minimum or no change in fuel use for the current system. In each case, it will be necessary to modify the design and/or operation of the system components. It is likely that not all recommendations can be implemented as shown in this report. However these recommendations can provide guidance for direction and future actions in installations at this or other locations.

3.3.1 Energy Efficiency Improvement

An analysis of the performance of the heat recovery components (boilers, raw meal dryer, coal feed mill, etc.) was carried out using data given in CBMA (2007a). Table 3 provides detailed analysis and results. Performance of the waste heat boiler is estimated using information for volume and temperature of exhaust gases from preheaters and part of the cooling air from clinker cooler. The heat of hot gases from preheaters and part of the air from clinker cooling is used to raise steam in boilers. Data collected during the visit shows that the boilers produce 22 tons steam per hour at 0.95 MPa pressure and 254 ^{o}C supply temperature. Total heat content of steam is 14.89 million kcal/hr. Assuming boiler heat recovery efficiency of 90%, total heat used from the gases would be 76.1 kcal/kg of clinker. These numbers are reconfirmed by considering power production and average heat used for power production. Results from these two approaches give very close results and indicate that total heat used in boilers is about 75 kcal per kg of clinker. In the following all quantities (such as kcal) stated as "per kg of clinker produced" are mentioned as kcal/kg-cl.

Boiler exhaust gases are used to dry raw meal, which contains 7% to 8% moisture as it enters the dryer. The moisture is reduced to 0.25% before feeding it to the preheaters. Moisture removal is very energy-intensive process. Calculations in Table 3 show that boiler exhaust gases should be at about 222 ^{o}C. During our visit, we were told that the plant expects this temperature to be between 220 ^{o}C to 150 ^{o}C. Exact temperature depends on operating conditions and temperature of gases entering the boiler.
As shown in Table 4, moisture removal or drying of raw meal from 8% moisture to 0.25% moisture requires 74.2 kcal/kgcl. Allowing for approximately 10% heat losses from piping and the dryer itself, total energy consumed from boiler exhaust gases is estimated to be 82.42 kcal/kgcl. Boiler gas temperature would drop by 45 ^{o}C with exhaust gas temperature from the dryer going to pollution control equipment would be 63.8 ^{o}C. During the visit, we were informed that the exhaust gas temperature is controlled to be at 100 ^{o}C to as required by the electrostatic precipitator (ESP) design. The plant sprays water in gases to maintain 100 ^{o}C gas temperature. Total heat content of the gases going to the ESP is 150.22 kcal/kg-cl.

Table 3. Analysis for Use of Heat Power Generation and Heat in Boiler Exhaust Gases Using Different Approaches

Heat in air from preheater	***823.4921***	***KJ/kg-cl***
Heat in air from cooler to cogeneration	***428***	***KJ/kg-cl***
Total heat in exhaust gases to boiler	1251.4921	KJ/kg-cl
Total clinker production	***217,469.00***	***kg/hr.***
Heat in air from preheater	179.08	GJ/hr.
Heat in air from cooler to cogen	93.08	GJ/hr.
Total heat in discharged air - boiler	272.16	GJ/hr.
	75.60	Mw
Power generated from waste heat	***6***	***Mw***
Efficiency of steam power generation	32.50%	% (See note below)
Effective energy use in boiler-turbine generator	18.46	
Waste heat in boiler stack	57.14	Mw
Waste heat in boiler stack	205.71	GJ/hr
Waste heat in boiler stack	945.91	kJ/kg of clinker
Waste heat in boiler stack	225.93	kCal/kg of clinker
Heat used for power generation	**72.99**	**kCal/kg of clinker**
Note: This is based on conversion: 1 kwh = 10,500 Btu for power production		

Average value of CP (sp. Heat) for ex. Gases	0.3352699	kCal/(Nm^3-deg. C.)
Total flow rate of exhaust air to boiler	3.0362	Nm^3/kg of Cl
Avg. temp of ex. Gases from boiler	221.94	Deg. C.
	431.50	Deg. F.
Heat in air from preheater after going through boiler	124.88	kCal/kg-cl
Heat in boiler stack exhaust contained in air from cooling bed going to cogeneration system	107.76	kCal/kg-cl
Total heat in boiler exhaust air	232.64	kCal/kg-cl

Steam production	22.00	tons/hr
Steam pressure	0.96	MPa
Steam temperature	254.00	Deg. C.
Enthalpy of steam	702.00	
Condensate water temp from Boile #2	25.00	Deg. C.
Enthalpy of condensate	25.00	Kcal/kg
Change in enthaly	677.00	Kcal/kg
Heat transfer in boiler	14,894,000	kcal/hr
Heat transfer in boiler	68.49	kCal/kgcl
Boiler efficiency	90%	Percent
Heat used in boiler	76.10	kCal/kgcl

** Data shown in bold italics was obtained from CBMA (2007a).*

Part of the clinker cooling air is used to dry-preheat coal fuel. Our observation is that this air is used to carry coal powder to the burners used in the kiln and precalciner. Hence, it is recycled to the kiln and should not be considered as a system energy loss. This air is used to heat coal, remove moisture, and at the same time maintain safety to avoid concentration of coal dust. This air is used to carry coal to burners. Hence, it is considered as recycling of heat in the system and not a loss.

Table 4. Analysis for Heat Recovery in the Raw Meal Dryer

Heat recovery in Raw Meal Dryer downstream of the boiler		
Gases from boiler go to raw meal dryer		
Raw meal moisture coming in	8.00	Percent
Mass flow rate of raw meal	350,000.00	kg/hr
Moisture in raw meal	28,000.00	kg/hr
Outgoing moisture in raw meal from dryer	0.25	Percent
Moisture content at the outlet of dryer	875.00	kg/hr
Moisture removed	27,125.00	kg/hr
Temperature of raw meal leaving dryer	45.00	Deg. C.
Heat required to remove moisture	539.00	kCal/kg of H2O
Heat required to remove moisture	14,620,375.00	kCal/hr
Raw meal temp. rise	20.00	Deg. C.
Specific heat of raw meal	0.22	kCal/kg raw meal
Heat used for raw meal temp. rise	1,505,000.00	kCal/hr
Total heat recovered in raw meal dryer	16,125,375.00	kCal/hr
Clinker production	1.61	kgcl/kg raw meal
Clinker production	217,391.30	kgcl/hr
Heat recovered in raw meal dryer	74.18	kCal/kgcl
Allowance for heat loss	10.00	% of heat recovered
Heat recovered + Heat loss for dryer	**82.42**	**kCal/kgcl**
Estimated temperature drop for exhaust gases in dryer	80.97	Deg. C.
Heat remaining in raw meal dryer exhaust gases going to ESP	**150.22**	**kCal/kg-cl**
Estimated temp. of exhaust gases out of dryer	147.57	Deg. C.

These calculations are used to prepare a new table for disbursement of heat as shown in Table 5. These values are represented in pie chart (Figure 3) format to give visual representation of relative magnitude of heat disbursement in the system. The pie chart indicates that major users of heat are: clinker formation, exhaust gases from the kiln discharged from the system, kiln surface heat loss, and power generation. Out of this, heat used for power generation should be considered as credit or negative energy use since it reduces the need to purchase electricity and the cost of electricity is much higher than the cost of coal.

Table 5. Summary of Heat Disbursed Including Use of Heat in Heat Recovery Equipment

Heat disbursed - Including heat recovery			
Item	kJ/kg	Kcal/kg	%
Heat of clinker formation	1,741.68	415.99	47.3%
Heat contnet of hot clinker	157.68	37.66	8.4%
Heat for vaporization of 0.25% water in raw meal (in the kiln)	9.73	2.32	0.2%
Heat used in the raw meal dryer for 8% moisture vaporization	345.07	82.42	6.4%
Heat in rawmeal dryer boiler exahust gases	628.93	150.22	12.5%
Heat carried out by hot dust	30.43	7.27	0.7%
Heat in air from clinker cooler to coal mill	102.86	24.57	2.4%
Heat used for power generation	305.58	72.99	7.2%
Heat loss from surface	341.97	81.78	8.7%
Incomplete combustion	20.06	4.80	0.6%

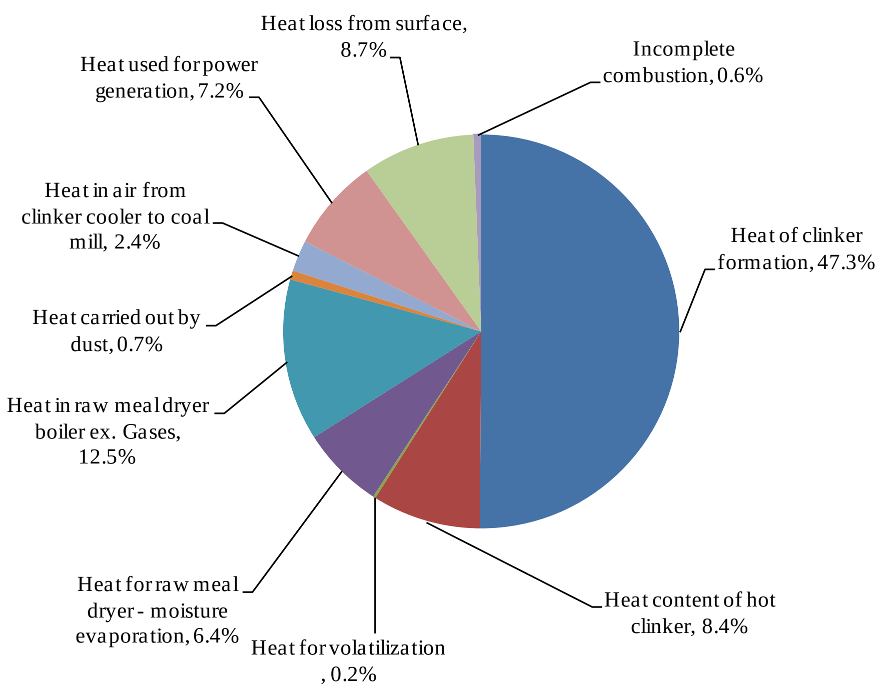


Figure 6. Heat Disbursement Including Use of Heat in Heat Recovery Equipment

Net heat loss from the system is included in following streams leaving the system:

- Hot clinker discharged from the cooler
- Hot dust leaving with exhaust gases to ESP
- Heat contained in hot exhaust gases to ESP
- Heat value in products of incomplete combustion (CO gas)
- Steam turbine condenser cooling water

Details of these losses are given in Table 6 below. Note that the percentage column represents the heat loss as a percentage of heat supplied by coal to the system. Heat supplied by coal is based on 0.1314 kg coal used per kg of clinker with coal heating value of 5,835 kcal per kg of coal. We should also consider the benefit of electricity generated from the cogeneration plant and take credit for equivalent heat. The cogeneration plant produces 6 MW electricity and at 10,500 Btu/kwh or 2,646 kcal/kHz energy use rate, this represents 72.99 kcal/kg-cl or 9.5% of heat supplied by coal. This 72.99 kcal/kg-cl should be subtracted from the total fuel supply to the plant which is 76.72 kcal/kg-cl. (in the form of coal). Hence net heat used for the plant is (766.72 minus 72.99) 693.73 kcal/kg-cl. This is equivalent to 119 kg coal per ton clinker. A graphical representation of these losses with their magnitude in terms of percentage of energy used from the coal is given in Figure 7.

Table 6. Summary of Heat Loss Expressed as Percentage of Heat Content of Coal Used in the System

Heat loss stream	kJ/kg-cl	kcal/kg-cl	% of heat input in the system
Hot clinker	157.68	37.66	4.9%
Dust	30.43	7.27	0.9%
Kiln surface heat loss	342.40	81.78	10.7%
Incomplete combustion	20.08	4.80	0.6%
Raw meal dryer exhaust	628.93	150.22	19.6%
Turbine condenser water	204.74	48.90	6.4%
Total heat loss from the system	1,384.26	330.62	43.1%

Total supplied in coal	**3,210.10**	**766.72**	**100.0%**
Eenrgy recovered in electric power In terms of equivalent energy used in power palnts	**305.58**	**72.99**	**9.5%**

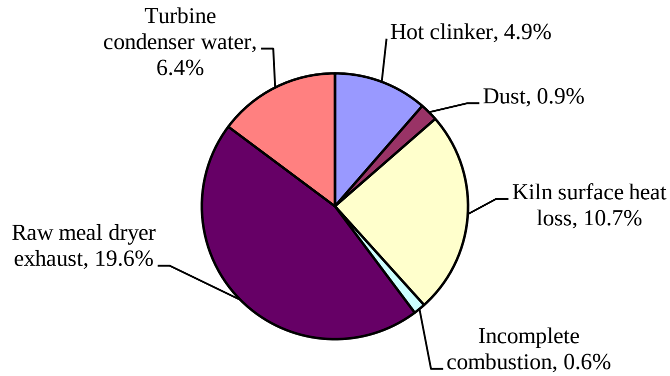


Figure 7. Heat Loss Expressed as a Percentage of Heat Content of Coal Used in the System

Energy use for the system can be reduced by analyzing how much heat is wasted in what areas and what steps can be taken to reduce the losses. Table 7 gives a qualitative evaluation of the possibility of reducing heat loss from the system.

Table 7. Areas of Heat Losses, Their Characteristics and Comments on the Possibility of Reducing the Losses

Type of Heat Loss	Loss as % of heat input	Temperature Level	Volume	Comment
Exhaust gases from raw meal dryer to ESP	19.6 %	Very low (about 100 deg. C.)	Very high (>35,000 Nm^3/hr). Includes excess air and air leakage.	This is very low-grade heat and gases cannot be cooled any further. However, reduction in air leakage will reduce this loss.
Kiln wall losses	10.7 %	High temperature (>450 deg. C.)	N/A	This is controllable by improving insulation –refractory for the kiln.
Heat in clinker	4.9 %	Medium (187 deg. C.)	Approx. 217,000 kg/hr	It will be difficult to cool clinker to a much lower temperature.
Heat in cooling water from turbine condenser	6.4 %	Very low, perhaps less than 25 deg. C.	Unknown	Not economically or practically recoverable
Heat in dust	0.6 %	Very low, perhaps less than 100 deg. C	Approximately 21,000 kg/hr)	Not economically or practically recoverable
Incomplete combustion – presence of CO in exhaust gases	0.9 %	Very low (about 100 deg. C)	<0.1% in exhaust gases	Can be reduced by improved combustion.

Two possible areas for reducing energy use are:

- Reduction in the volume of exhaust gases

- Reducing kiln surface heat losses.

The potential for both of these possibilities is analyzed to get a value of the minimum energy use or coal use in this system.

Exhaust gas volume or mass flow reduction

Exhaust gases represent a large percentage (19.6%) of the total heat input or coal used in the system. Analysis of reduction in exhaust gas is shown in Table 8. Exhaust gases can be reduced by reducing the use of excess air for coal combustion in burns and by eliminating (or reducing) air leaks in the system. At this time coal combustion uses about 35% excess air. It is possible, particularity with use of hot combustion air, to reduce excess air from 35% to 20% with proper burner design and operation. The system air leak is about 29% of the total exhaust gas volume. Eliminating this air leakage would reduce exhaust gas flow and hence heat contained in these additional volume of gases. The effect of both of these steps is to reduce coal consumption by 8.06 kg coal per kg of clinker production.

Reduction of kiln surface temperature

The kiln surface temperature varied from 400 ^{o}C to as high as 500 ^{o}C. This is confirmed by checking calculated values of surface heat losses reported in the CBMA (2007a). These values were checked by using alternate source (PHAST program developed by U.S. Department of Energy). The wall loss calculation was made by using the PHAST program, Figure 8 shows that by reducing current heat loss, energy consumption of 75.57 million kJ/hr (342 kJ/kg-cl) can be reduced to approximately 28.27 million kJ/hr (130 kJ/kg-cl) if the kiln surface temperature is reduced to about 300 ^{o}C. The kiln surface area is 1,115 m^2 and the ambient temperature is 25 ^{o}C. This will reduce overall surface heat loss from 10.7% (of the heat input) to about 4%. The difference (6.7%) could reduce coal use by 7.97 kg coal per kg clinker.

If we can use both energy-saving measures discussed above, then total coal use can be reduced by 16.03 kg/kg-cl (7.97 kg/kg-cl plus 8.06 kg/kg-cl). The final coal use could be as low as (119 kg-coal/kg-cl minus 16 kg-coal/kg-cl) or 103 kg-coal/kg-cl. Note that this is a target and it may be necessary to conduct further investigation in available materials and installation of multiple layers of refractory insulation to achieve lower surface temperature.

Table 8. Calculations to Estimate Reduction in Coal Use Associated with Exhaust Gas

Volume of CO2 released		
Ratio Raw meal to clinker	1.61	
Raw meal used	350125	kg/hr.
Clinker production	217,468.94	kg/hr.
Loss of material in kiln	132,656.06	kg/hr.
Density of CO2 equivalent gas	0.117	lb/ft^3
	1.8742	kg/Nm3
Dust loss recorded	21,007.50	kg/hr
CO2 volume from loss of material in kiln	59,572.59	Nm3/hr
CO2 volume from loss of material in kiln	0.27	Nm^3/kg-cl
Exhaust gas volume	1.5881	Nm^3/kg-cl
Exhaust gas volume minus CO2 volume	1.3142	Nm3/hr
Average O2% in preheater exhaust gases (dry)	4.8	
Corrected value of O2 in combustion products	5.80	%
Excess air used	35%	from graphs
Recommended air	20%	
Reduction in volume of combustion products	**11%**	
Reduction in combustion products volume	**0.0933**	**Nm^3/kg-cl**
Ex. Gases from preheater	1.5881	Nm^3/kg-cl
Air flow leakage in the system	0.4562	Nm^3/kg-cl
Air leak reduction possible	**29%**	
Possible reduction in exhaust gas volume	**0.5495**	**Nm^3/kg-cl**
Total volume reduction potential	35%	
Current heat loss in exhaust gases as % of coal heat input	19.59%	
Reduction in heat input based on current exhaust gas heat losses	6.78%	
Current net coal use (coal feed rate minus credit for power generation)	118.89	kg coal/ton of clinker
Possible reduction in coal use	8.06	kg coal/ton of clinker
Coal use with elimination of losses and improvement in combustion condition	110.83	kg coal/ton of clinker
Reduction in coal use with lower kiln surface heat losses	9.00	kg coal/ton of clinker
Coal use with reduction of kiln wall losses, elimination of losses and improvement in combustion condition	101.83	kg coal/ton of clinker

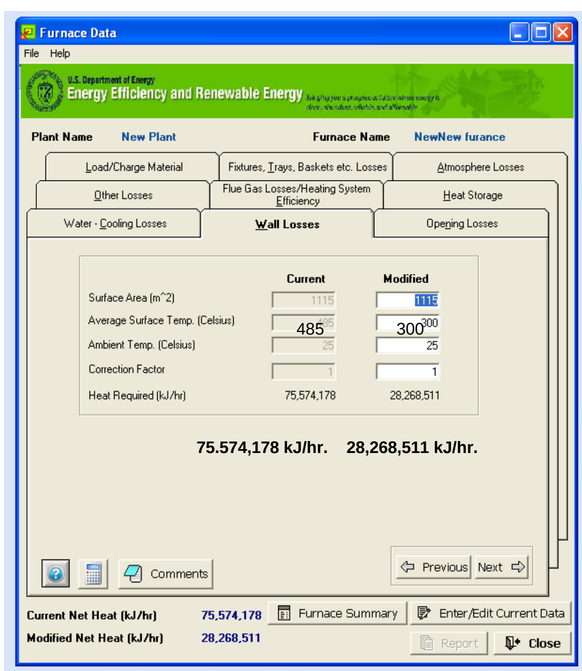


Figure 8. Calculations for the Kiln Surface Heat Losses

3.3.2 Emission Reduction

The CBMA report includes data on the composition of exhaust gases leaving the preheaters (CBMA, 2007a). Table 9 shows the presence of a small amount (0.1%) of CO. However this reading is taken in gases that contain combustion products of coal, additional air from various sources, and CO_2 produced during calcining process. The actual volume of combustion products is proportional to coal used. Based on information given in Table 9, the actual CO generated during combustion process is 0.19% (Table 10).

Table 9. Exhaust Gas Analysis (Wet Basis) (CBMA 2007a)

Test time	CO_2	O_2	CO	N_2	H_2O	α
1	22.2%	7.0%	0.1%	70.7%	4％	1.56
2	30.8%	3.2%	0.1%	65.9%	4％	1.22
3	29.2%	4.2%	0.1%	66.5%	4％	1.31
average	26.3%	4.6%	0.1%	65.0%	4.0%	1.36

Table 10. Calculations for CO Produced from Combustion Source – Coal Burners

Stoichometric air	0.8401	Nm^3/kg-cl
Ex. Gas from preehater	1.5881	Nm^3/kg-cl
Ex. Gas minus CO2	1.3142	Nm^3/kg-cl
Co in preehater exhaust agses	0.10%	Percent
Co content corrected for addiitoanl volume of gases	0.19%	Percent

Data on the presence of any other pollutants (i.e. hydrogen, hydrocarbons etc.) was not collected during this assessment. Hence it is not possible to provide values of these pollutants. However even the 0.19% CO generation in coal combustion in a high temperature process with use of 35% excess air is unusual. We do not know whether this CO is generated in the kiln or in the precalciner or at both locations.

However it is very likely that the entire amount or majority of it is produced in precalciner. Combustion conditions in the precalciner are not as "good" – defined by higher temperature, good mixing, and long residence time – as in the kiln. It is highly unlikely that CO can survive in percentage quantities under conditions existing in the kiln. However this needs to be checked by taking a CO reading in exhaust gas stream from the kiln before it enters the precalciner. Conditions in the precalciner coal combustion are not as good as in the kiln. In this area air and gases from different locations are mixed, the residence time for coal combustion is relatively small, combustion zone temperature is much lower, and residence time for gases at higher temperature is much shorter. It is necessary to take gas analysis at several locations, particularly at the outlet of precalciner to confirm this.

It is unlikely that CO is generated anywhere else in the system since gases in all other areas are at much lower temperatures and no additional combustion takes place. Hence the main area to focus on to reduce CO emission, and perhaps other pollutants, is the combustion zone for the precalciner.

3.4 Suggested Actions to Reduce Energy Use and Reduce Emission of Pollutants

3.4.1 Reduction in Volume of Exhaust Gases

This has a potential of reducing energy used for heating excess amount of air discharged as exhaust gases. It is necessary to use less air for combustion in coal burners and control negative pressure at all places in the system components. Reduction of openings and gaps also would reduce air leakage. It is necessary to perform leak tests at several locations, particularly close to areas near the induced draft (ID) fan where negative pressure is relatively high.

At this time coal combustion uses about 35% excess air. It is possible, particularity with use of hot combustion air, to reduce excess air from 35% to 20% with proper burner design and operation. The system air leak is about 29% of the total exhaust gas volume. Eliminating this air leakage would reduce exhaust gas flow and hence heat contained in these additional volume of gases. The effect of both of these steps is to reduce coal consumption by 8.06 kg coal per kg of clinker production.

3.4.2 Reduction of Kiln Surface Heat Losses

The kiln wall loss calculation made by using the PHAST program shows that the current heat loss (342 kJ/kg-cl) can be reduced to approximately 130 kJ/kg-cl if the kiln surface temperature is reduced to about 300 ^{o}C. This will reduce overall surface heat loss from 10.7% (of the heat input) to about 4%. The difference (6.7%) could reduce coal use by 7.97 kg coal per kg clinker.

The assessment results indicated a moderate value of CO (0.1%) in exhaust gases. The source of CO generation is not known. However it is suspected that combustion conditions in the precalciner are conducive to production of CO due to incomplete combustion of carbon from coal or “quenching” of flame are responsible for CO in the exhaust gases. The location of the exact source and actions required to eliminate or greatly reduce CO formation will require additional data collection, aimed specifically at addressing the CO emission issue. It is very likely that any other pollutants present in much smaller quantities are directly related to the formation and presence of CO.

4. Energy and Emissions Assessment for a Vertical Shaft Kiln at Shui Ni 2 Cement Plant[5]

The Shui Ni 2 cement plant uses 9 VSKs for producing clinker, the key material used for cement manufacturing. This study was conducted on Shui Ni 2's VSK #2, which is a relatively small kiln with average clinker production capacity of 16.5 tons per hour. The plant is equipped with a fabric filter air pollution control device. Emissions of polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDDs/PCDFs) from this kiln were previously measured at 0.518 nanograms toxic equivalence (ng TEQ)/m3. Chinese emissions standards for both existing and new units are 0.1 ng TEQ/m3 and U.S. standards are ≤ 0.016 ng TEQ/m3.

4.1 Process and Equipment Description

A simple schematic of the kiln with critical areas is shown in Figure 9. The VSK has an outside diameter of 4.6 meter (m) and height of 7.5 m. The upper section of the kiln consists of a cone shape with an upper diameter of 5.2 m, lower diameter of 3.2 m and height of 2.5 m. The kiln is connected to a bag house that is used as control device for particulates emitted from the kiln. No additional control device is used to control emissions of gaseous pollutants from the kiln.

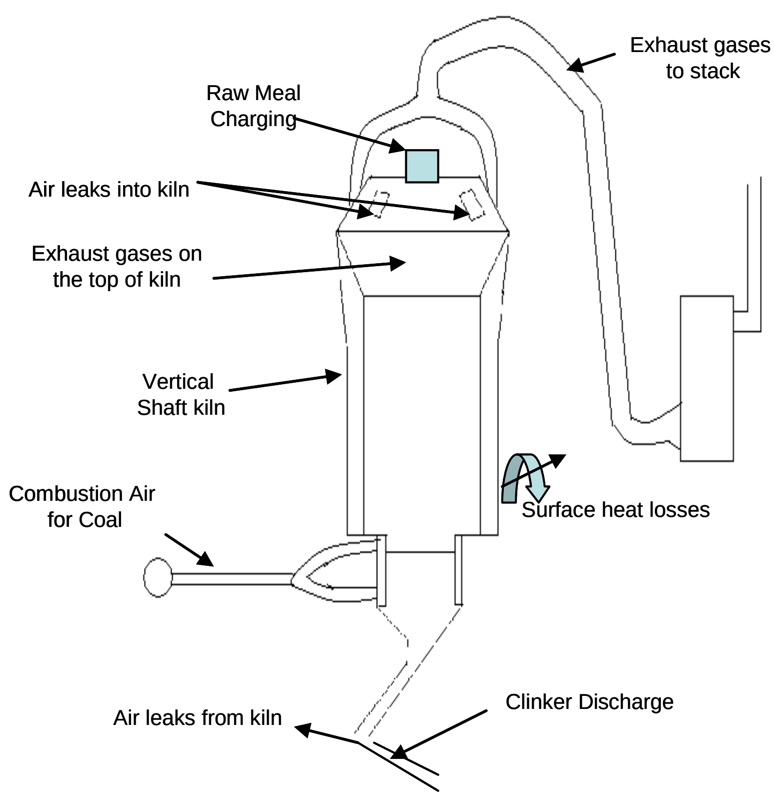


Figure 9. Simple Schematic of the Vertical Shaft Kiln (VSK)

[5] This section is excerpted from the report prepared by Arvind Thekdi, E3M, Inc.

Raw material for clinker production includes limestone ($CaCO_3$) mixed with other materials such as sand, magnesium carbonate, and coal dust. The materials are mixed with water and formed into small nodules (pallets) that contain 11.7% moisture with 8% coal.

The nodules are formed at ambient temperature (25 °C to 30 °C in this case) and are charged at the top of the kiln by a rotary feeder. The nodules move downward through the kiln by gravity while the material flow rate (kg/hr) is controlled by the rate at which clinker is removed from the bottom of the VSK. A rotary valve at the bottom of the kiln controls the discharge rate of the clinker. The clinker discharge opening is not very tightly sealed and could leak the hot gases out or may allow cold air introduction in the kiln body. The flow rate of leaking air though the kiln is controlled by pressure at the valve location. The pressure was negative during this assessment, resulting in airflow entering into the kiln.

Combustion air used for coal combustion and generation of heat within the kiln is blown into the kiln. The air is at ambient temperature and is pressurized by an air fan or blower before entering the kiln at two locations. The majority of the combustion air, usually more than 80% of the total air, is distributed through a number of air nozzles at the bottom of the kiln where it then travels upward through the bed of clinker and raw meal, successively. Another portion of the air (less than 20%) is distributed at the mid-section of the kiln and is mixed with the air traveling upward from the bottom. Distribution of the airflow affects the temperature distribution within the bed, the quality of clinker, and the carbon content of clinker.

The air is heated as it is exposed to the hot material traveling downwards and reaches a high enough temperature to initiate reaction with carbon in the coal to produce heat of combustion. The amount of heat produced, the temperature of the reaction, and the composition of the combustion products depends on the relative amount of air and coal, reaction time, and the temperature of the reaction. In most cases, there is sufficient air and oxygen available to complete the reaction of carbon in the coal in the mid-section of the kiln. The combustion products that now include primarily carbon dioxide (CO_2) and nitrogen (N_2) with small amounts of carbon monoxide (CO), hydrogen (H_2), water vapor (H_2O) etc. travel further up through the bed.

A very simplified picture of the temperature profile of the raw material nodules and the air used in the kiln is shown in Figure 7. The kiln can be divided into four separate zones or sections. The location and size (volume) of these zones depend on a number of factors related to operation of the kiln. However, they are always present in a well-designed and operating kiln. The zones, referred to as the charge and air leakage zone, the upper zone, the middle zone, and the lower zone, are discussed below.

Raw material (or nodules) is charged in the uppermost section, identified as charge and air leakage zone, of the VSK. In this zone, hot gases from the bed of raw material are mixed with ambient air leaking into the VSK. Pressure in this zone is negative due to the suction created by the induced draft (ID) fan. Gases from the bed are relatively cold, usually less than 500^0 C., and cannot react with O_2 in air. Hence the composition of gases discharged from the bed is “frozen” or unchanged downstream of this zone.

The raw material, or nodules, charged in the charge and air leakage zone (as described above) form a bed in the VSK. The top part of this bed is referred to as the upper zone. The hot gases from the middle zone travel in the opposite direction (bottom to top) of the direction of travel (top to bottom) of the nodules. As the raw material flows downward, its temperature increases and temperature of the gases from the lower sections drop due to heat transfer from the hot gases to the cold material. This results in preheating as it recovers heat from hot gases. Airflow through the bed and, in some cases air introduced in the middle section of the kiln, is more than sufficient to complete the reaction of carbon to produce CO_2. However as the hot gases (CO_2 and N_2 primarily) travel upwards, they continue to be in contact with incoming material. They transfer heat to the material to increase the material temperature and evaporate water contained in the nodules. The free or residual oxygen that remains from the reactions in the lower section as well as CO_2 generated in the middle and lower section react with carbon (C) in the nodules.

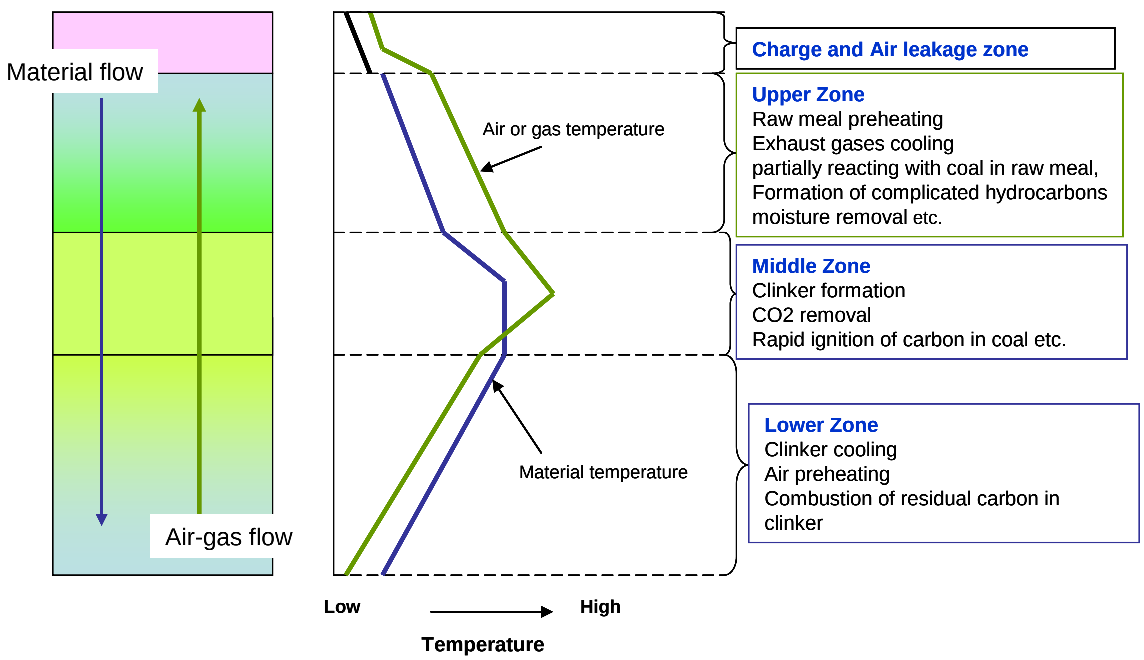


Figure 10. Illustration of Typical Temperature Profile for the Material and Air or Combustion Gases in the VSK

There are several other reactions taking place in the upper section and they result in production of heavy to light hydrocarbons and other compounds that are difficult to predict. A number of factors (time, temperature, relative percentages of CO_2 and CO, etc.) affect these reactions. These reactions may occur only in a short length (height) of the bed and stop as the temperature of the gases drops.

Volatile material consisting of heavy hydrocarbons from coal is also released in the upper and middle zones of the kiln. Some of this volatile material may react with hot air and some of it, particularly the volatile gases released in the upper section of the kiln, will not have an opportunity to burn. The unburned volatile material in the form of simple or complex hydrocarbons, and other compounds including available halogens or other elements, becomes part of the exhaust gases from the kiln. However once the compounds are formed, they cannot be removed and they become part of the exhaust gases at the top of the bed. It should be noted that water from the surface of the nodules vaporizes in the upper section of the kiln and may continue to vaporize as nodules are heated from the surface to the core and water continues to come out of the nodule.

The middle zone can be considered as the primary reaction zone where heated air reacts with carbon in the nodules and raises the temperature of the air or combustion products and nodules to very high level, exceeding 1000 °C. The higher temperature of the nodules results in a calcining reaction for the carbonates which is highly endothermic and requires a considerable amount of thermal energy (approximately 1795 kJ per kg of clinker produced) to complete. During the calcining reaction, a large amount (approximately 44% to 48% of the weight of the raw material charged) of CO_2 is produced. The CO_2 mixes with gases produced from combustion of coal and moisture vaporized from the raw meal. The gas mixture is collected at the top of the bed.

The calcined hot material, clinker, flows downward in the lower zone where it is in contact with air introduced at the bottom of the kiln. Due to the large surface area of the material, air is heated as it flows upward. Some of the air may react with residual carbon in the clinker where the clinker surface temperature is high enough for carbon-oxygen reaction, approximately 800 °C. This section is used for recovering heat from the clinker and heating air that is required for combustion of carbon in middle section. Figure 8 provides a summary of above discussion.

A large amount of cold air is introduced in the kiln at the top of the bed in the upper section of the kiln due to negative pressure and openings at the top of the kiln. This air is mixed with gases coming out of the charge material, which results in dropping the gas temperature and increasing the O2 percentages in the exhaust gas. In most cases, this is desirable since it is necessary to control the gas temperature at a low value (usually about 100 °C or lower) before the gases pass through a pollution control device such as the bag house used for this VSK.

The above discussion assumes a simplified sequence of chemical reactions. It shows that a shaft furnace using coal or another type of solid fuel will always produce products of incomplete combustion (CO_2, H_2 etc.) together with a number of complex hydrocarbons that resemble dioxin and other compounds. In many cases, as in case of the VSK, the reaction products do not have sufficient time and high enough temperature to complete the combustion reaction due to the successively lower temperatures encountered as the gases travel upward in the kiln. Hence, it is common to find complex hydrocarbon compounds in coal-fired VSKs.

Although this assessment did not measure emissions from the VSK, past assessments carried out on this and similar VSKs clearly show that the kiln exhaust gases are a source of number of pollutants such as dioxin, CO, particulates, and unburned hydrocarbons. These tests and analysis of the data indicate that the presence of pollutants is directly related to incomplete combustion reactions between carbon-bearing materials (coal) and partial combustion products such as CO_2 and H_2O.

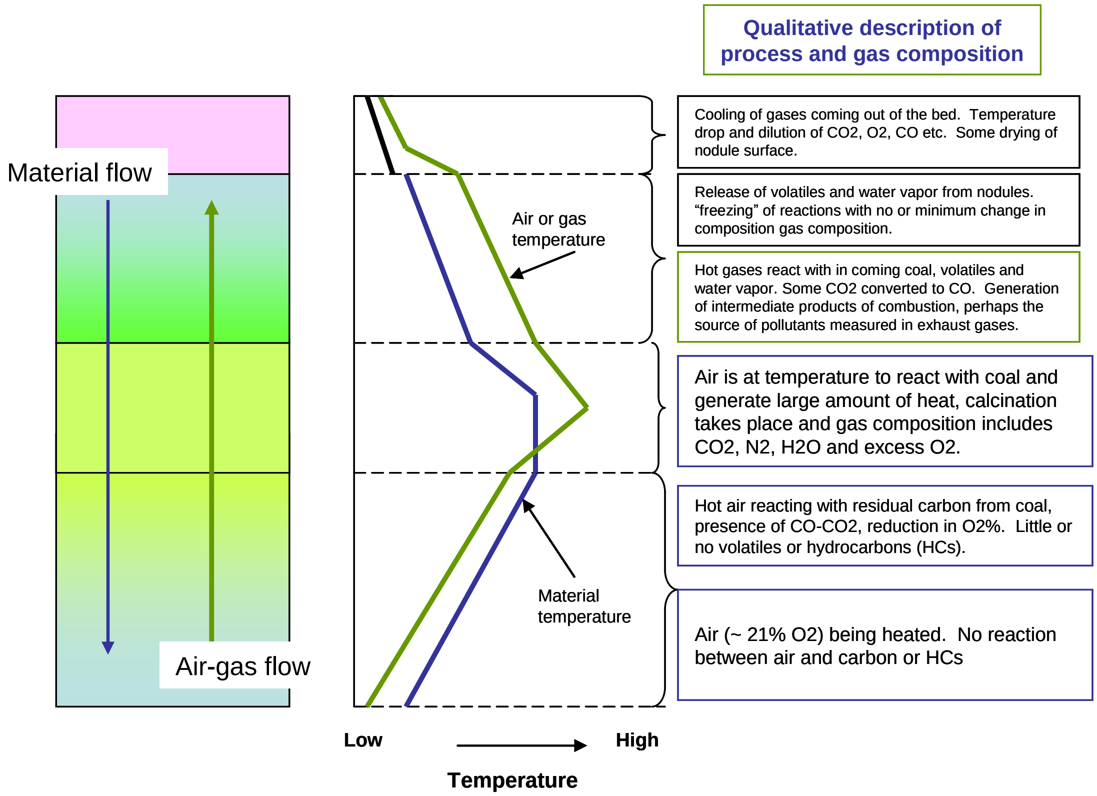


Figure 11. Qualitative Description of Process and Gas Composition in a Typical VSK

The kiln design includes a continuous heat recovery process and is relatively energy efficient. The design, however, also results in the generation of pollutants due to its tendency to produce and freeze intermediate products of the combustion reactions at the exhaust gas outlet. This phenomenon is common for other similar types of equipment used in the industry. Prime examples are older designs of garbage incinerators that were major sources of dioxins, iron-making cupola furnaces used in iron foundries, blast furnaces used in the steel industry, and vertical shaft calciners used for coke calcining. In each case, the operating companies had to take steps to further process the exhaust gases or to use the gases for supplying heat to other processes in order to avoid formation and release of such pollutants. For example, garbage incinerators and cupola furnaces used thermal oxidizers or incinerators to raise the exhaust gas temperature above 760 °C while blast furnaces and coke calciners used exhaust gases as a fuel source in other equipment.

Air or exhaust gas flow in a vertical shaft furnace also results in entrainment of small particles from the material bed. A simple calculation for this VSK indicates that superfecial velocity (velocity of gases calculated based on total open area of the inside of the kiln) exceed 0.5 m/sec. We do not have exact data for components of the raw meal but if we use data for sand particles (higher density than the materials in the raw meal), it is clear that at this velocity any particle above 0.1 meter or 100 micro-meter would have a good chance of fluidizing and thus get into the exhaust gases. The presence of 192.2 kg/hr dust (0.01116kg/kg of clinker), representing about 3,287 parts per million (ppm) based on mass ratios of dust to the exhaust flow (CBMA 2007b). This is considered very high and needs to be controlled by control measures either in the VSK itself or outside the VSK.

4.2 Measurements and Estimate of Energy Distribution

The CBMA report includes values of several key parameters that allows for development of a heat and material balance of the kiln (CBMA, 2007b). A summary of the data collected by the CBMA team in Shui Ni 2 cement plant for VSK is shown in Table 11.

Table 11. Summary of Data Collected by CBMA Team at Shui Ni 2 Cement Plant (CBMA 2007b)

No.	Measurement contents	Items							
		p	t_g	t_m	C_f	C_g	Loss	G_m	φ_m
1	Air to kiln	√	√						
2	Clinker exited from Kiln		√	√			√	√	
3	Leaky air via discharge pipe		√						
5	Exhaust gas at the top of kiln					√			
6	Raw meal nodule fed in kiln			√					√
7	Exhaust gas exited from chimney	√	√		√	√	√		√
8	Circumstance	√	√						
9	Raw meal						√	√	√
4	Heat loss from the surface of kiln body √								
10	Coal proximate analysis, coal ash analysis								
11	The chemical composition analysis of raw meal, clinker, and the physical properties analysis of clinker								

In the table：p－pressure tg－the temperature of gas tm－the temperature of material C_f－dust content
Cg －exhaust gas composition Loss－Loss of ignition Gm－material flow φ_m－Moisture content of materials

A summary of heat used or wasted in the VSK is shown in the following chart (Figure 9). The chart shows that almost 70% of the heat supplied is used for drying (vaporization for nodule water), heating (hot clinker) and calcining (clinker formation) of the raw meal or nodules. Almost 20% of the heat is wasted due to inefficiencies in combustion process (chemically and mechanically incomplete combustion of coal) (CBMA 2007b). The CBMA report has not accounted for heat loss due to presence of hydrocarbons in the exhaust gas. Hence the term Exhaust gases do not include heat loss due to presence of unburned hydrocarbons etc. in exhaust gas. Further calculations, described later in this report, show that this loss is as much as the loss due to presence of CO, described below as "chemically incomplete combustion of coal". Including this makes the total loss associated with inefficient combustion more than 25% of total heat supply to the kiln.

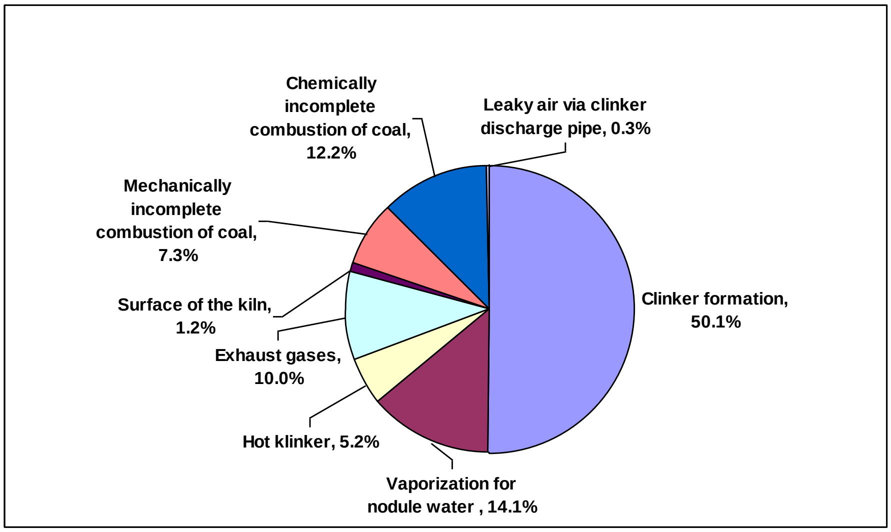


Figure12. Distribution of Energy Use or Losses in the VSK (CBMA 2007b).

Results of further analysis give information on heat used for the calcining process, heat used for raising temperature of raw material, heat of water vaporization, and other losses such as surface heat losses and heat contained in incomplete combustion of coal. The following pie-chart (Figure 13) and Sankey Diagram (Figure 14) provides the distribution of heat used and areas of major heat losses in the VSK based on the PHAST analysis.

The PHAST analysis accounting is slightly different from the heat balance used in the CBMA report. However, there is very good agreement in areas major non-process related heat losses. For example the wall losses are 1.2% in each case and negligible. The other losses calculated using PHAST due to unburned carbon (referred to as mechanically incomplete combustion) and CO in flue gases (referred to as chemically incomplete combustion) are very close to the losses calculated by CBMA (19.6% in the CBMA report vs. 20.2% in PHAST). Differences in exhaust gas loss (10.0% in the CBMA report vs. 14.7% in PHAST) seem to be due to differences in accounting of heat in water vapor. PHAST does not consider all water vapor as part of exhaust gases since heat lost in water vapor from the raw meal is considered as part of the heat required for load. A comparison of different terms used in the CBMA report and the PHAST is given in Table 12.

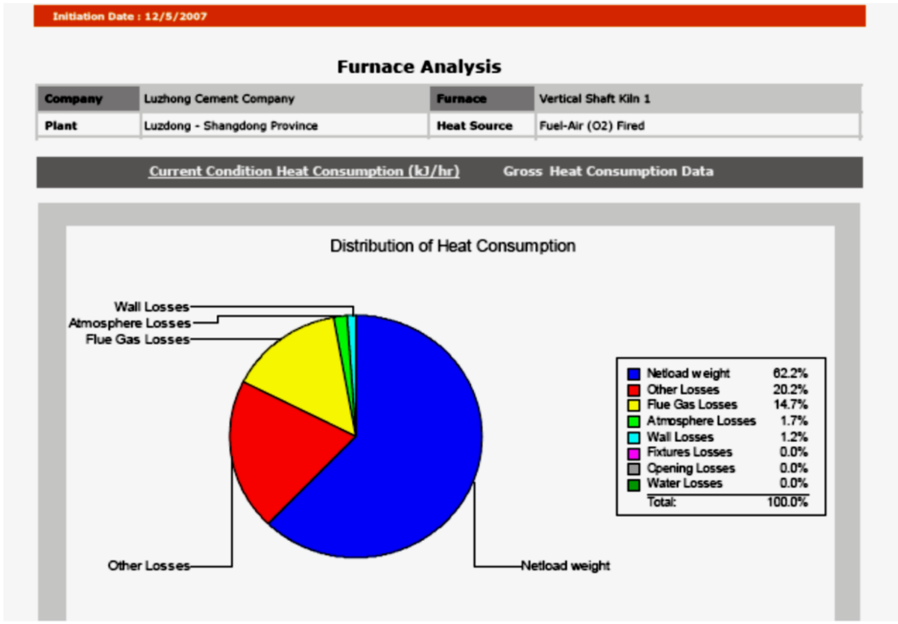


Figure 13. Energy Use Distribution for the VSK Using PHAST Software Program

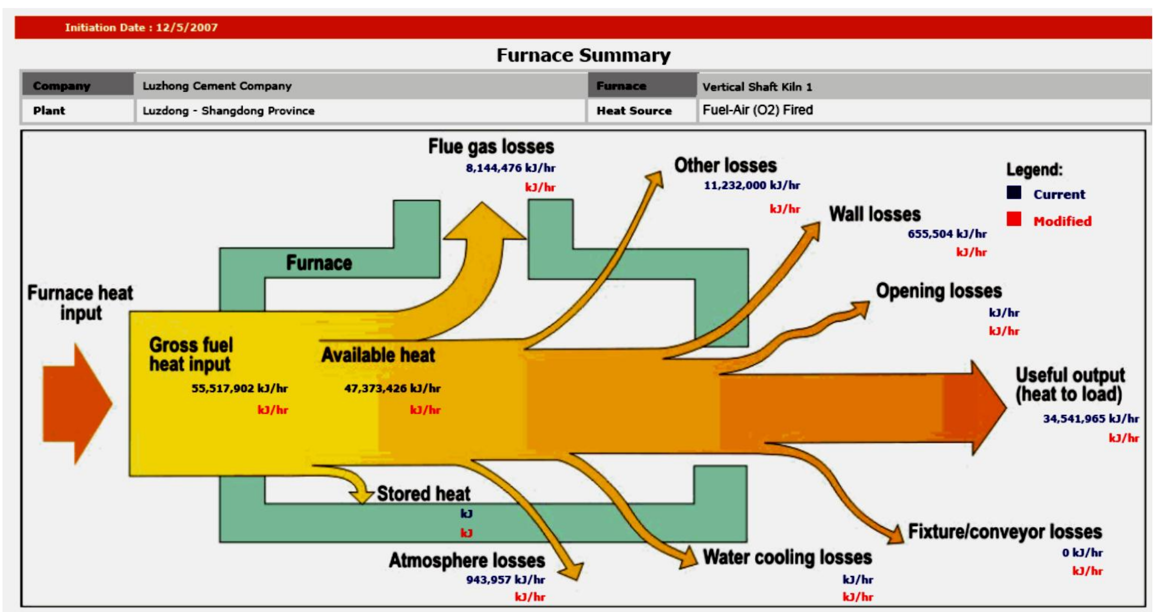


Figure 14. "Sankey' Diagram Showing Energy Supply and Distribution for the VSK.

The total heat required for the process calculated by PHAST and given in CBMA report is very close. The CBMA report concludes that total heat delivered from coal is 53.67 GJ/hr while the heat requirement calculated by PHAST is 55.5 GJ/hr. This represents a difference of about 2%. Considering the assumptions, the results of these two different approaches are very close. The significance and impact of these results are discussed in the next section.

Table 12. CBMA Report and PHAST: Comparison of Terminology Used and Results

CBMA Report Results: Heat Loss Category	Percentage of Total	sum	sum	Percentage of Total	PHAST Report Results: Heat Loss Category
The heat in clinker formation	50.1				
Heat with discharged clinker	5.2	63.6	62.2	62.2	Net load weight heat
Heat for vaporization of water *	8.3				
Mechanically incomplete combustion heat loss	7.3	19.5	20.2	20.2	Other losses
Chemically incomplete combustion heat loss	12.2				
Heat loss from the surface of kiln	1.2	1.2	1.2	1.2	Wall losses
Exhaust gas loss	10.0	15.9	16.4	1.7	Atmosphere loss (CO2 heat)
Heat for vaporization of water*	5.9			14.7	Flue gas loss
Total with rounding error		**100.2**	**100.0**		**Total with rounding error**

* Notes:
Total heat for vaporization of water in nodules is divided for heat required to evaporate water from nodules and heat in flue gases due to combustion of volatiles etc. from fuel. Total heat remains 14.1 % as reported in CBMA report

4.3 Analysis and Recommendations

The discussion for improving VSK performance is divided into two sections. The first section deals with energy reduction through energy efficiency improvements and the second section addresses reduction of pollutants with minimum or no change in fuel use for the current system. In each case, it will be necessary to modify design and/or operation of VSK. Since there are a large number of VSKs operating in China, it may be necessary to initiate a program that would develop components for retrofit on existing VSKs after testing the changes on a pilot test unit.

4.3.1 Energy Efficiency Improvement

Energy use or losses in the VSK fall into three major categories:

a) Energy used for processing the raw material that is converted into clinker. This requires a supply of heat for (i) energy required for calcination reaction, (ii) vaporizing of water in nodules, and (iii) energy used for hot clinker discharged from the kiln.
b) Heat loss in exhaust gases. This loss includes sensible heat in exhaust gases due to its mass and temperature. Exhaust gases include products of coal combustion, CO_2 generated in the calcination reaction, and water vapor.
c) Heat losses resulting from incomplete combustion of coal or unburned carbon discharged from the kiln, gaseous pollutants such as CO_2 hydrocarbons, and other compounds such as dioxin that have been measured in previous tests.
d)

In addition, there are relatively small kiln surface heat losses and other miscellaneous losses from openings. There is very little, if anything, that can be done economically to reduce these losses. Each of the three main categories of heat use/loss is discussed below.

a) Energy used for processing the raw material that is converted into clinker.

The largest amount of heat, about 50% of total used in the kiln, is used for supplying energy required for calcination. Calcination is an endothermic process and requires 1795 kJ/kg of clinker. This is a basic requirement for the process, and the only way to change this heat requirement is to change composition of raw material used. This cannot be done unless major changes are made to the cement-making process. It is highly unlikely that this could happen in near future.

Vaporizing of water used as part of the nodules or charge material represent about 14% of the total heat. Water evaporation requires a very large amount of energy (>2150 kJ/kg) and any step to lower the use of water in nodule preparation would save considerable energy and, at the same time, reduce the volume of exhaust gases from VSK. With the current operations, mixing of raw materials with water is an integral part of the process and it would be difficult to eliminate use of water. However, it may be possible for the plant to investigate effect of using less water. Calculations for heat demand show that reduction of water content of the nodules from 11.17% to 10% would reduce energy use by about 1.1%.

Another possible step that could reduce energy use for water evaporation in the kiln is to pre-dry nodules by using heat from exhaust gases to reduce the energy used in the kiln itself. Pre-drying of charge material is commonly used in mineral processing industries where pellets or briquettes are used for production of minerals and are pre-dried before charging them into the heating process equipment (kiln or furnace). Pre-drying of nodules using waste heat from the kiln and/or hot air use to cool clinker (discussed later) would reduce the amount of water vaporized in the kiln itself and thus reduce the use of heat required from coal combustion. It is necessary to redesign the area where the nodules are charged and exhaust gases are discharged from the kiln to accomplish such pre-drying.

Clinker is discharged from the kiln at about 222 °C and the net amount of heat contained in the clinker is relatively small due to very efficient heat recovery in lower part of the kiln. In this section hot clinker exchanges heat to combustion air that flows in a counter-current direction to the flow of clinker. Clinker temperature can be further reduced by increasing the residence time of the clinker and increasing the air flow through the hot clinker thus increasing the heat transfer in the kiln. This is not a good approach because it will increase exhaust gas flow and correspondingly exhaust gas heat loss. Clinker can also be cooled after it is discharged from the kiln, which would require redesign of the discharge area and site-specific solutions. In the case of the Shui Ni 2 VSK #2, it is possible to use the air flow in the ducts carrying clinker and recover part of the heat for pre-drying nodules or heating water. However, the amount of heat that will be recovered is very small. It is difficult to estimate exact savings due to lack of all necessary data. Additionally this requires major design changes for the system.

b) Heat Loss in Exhaust Gases

This loss includes sensible heat in exhaust gases due to its temperature and mass flow. Heat loss in kiln exhaust gases represent 10% of the total heat used in the process. This loss depends on the mass (volume) flow of combustion air supplied to the kiln, air leakage through clinker discharge area, CO_2 produced in calcining process, and water vapor produced by evaporation of water in the nodules. This loss can be reduced by reducing the mass flow of the exhaust gases and/or the temperature as the gases exit the kiln bed itself. Data for air flows indicate that total air flow, including air leakage through the clinker discharge area, is not excessive and it is not possible to change CO_2 generated in the process. Hence, the only possibility is to reduce water vapor from the nodules. As mentioned earlier this would require reduction in the water content of the nodules or pre-drying of the nodules.

Exhaust gases discharged from the kiln include air leakage on the upper section of the kiln. The volume of air leakage is about twice the volume of gases discharged from the kiln bed. Mixing of ambient air with kiln gases reduces the exhaust gas temperature from about 230 °C to 94 °C. Reducing the amount of air leakage on the top of the kiln will not reduce exhaust gas heat losses. However, as discussed later, returning of pollutants such as CO and combustibles present in the exhaust gases from the bed would increase exhaust gas temperature significantly (>760 °C) and it is possible to recover a significant amount of heat from these hot gases.

c) Heat losses resulting from incomplete combustion of coal or unburned carbon.

The CBMA report indicates that the second largest amount (about 20%) of energy loss is due to incomplete combustion of coal as reflected in presence of CO exhaust gases and unburned carbon (CBMA, 2007b). The CBMA report also indicates that heat loss due to the presence of CO is about 12.2%. This loss is associated with presence of hydrocarbons, measured as 0.37% in exhaust gases. The PHAST results (Table 13) show heat loss due to CO in exhaust gases as 7.36 GJ/hr, while the CBMA report shows it as 7.1 GJ/hr. This can be considered as good agreement between the two values. Heat loss due to the presence of hydrocarbons is estimated to be about 6.01 GJ/hr. This is significant amount since it represents about 10.4% of the total energy used.

Thus, it is likely that total loss due to presence of CO and hydrocarbons is substantially higher and it is important to consider steps that could reduce this loss. In addition to the energy loss, the presence of CO and hydrocarbons indicates the presence of other pollutants as confirmed by previous tests on VSKs. Preliminary calculations, discussed in the next section, show that presence of CO and hydrocarbons can be used to supply almost 2/3^{rds} of the heat required for raising exhaust gas temperature to 900°C. Note that this assumes that reburning takes place above the bed before air leakage into the kiln. Additional fuel required to accomplish this is about 6.5 GJ/hr and it has to be supplied by coal or other fuel sources. However, exhaust gases produced from reburning process would contain total heat of 18 GJ/hr and, with economically and practically achievable heat recovery efficiency of 65%, this would offer 11 GJ/hr of heat that can be used to preheat air and/or water used in the plant and process.

Table 13. Calculations to Estimate CO and Hydrocarbon Content of Gases Above the Raw Meal or Material Bed in the VSK

Heat Loss due to HC in Exhaust Gases		**Unit**
% HC in cooled exhaust gases	0.37	%
volume of exhaust gases	43631	Nm3/hr
HC in Ex gas	161.4347	Nm3/hr
HC in Ex gas	5,700	cfh
Heating value of HC	1000	Btu/scf
Heat in HCs	5.70	MM Btu/hr
Heat in HCs	6.01	GJ/hr
Heat Loss due to CO in Exhaust Gases		
Heating value of CO	320	Btu/scf
CO % in ex. Gases	1.4	%
Volume flow of ex. Gas	43631	Nm3/hr
Volume flow of ex. Gas	1,557,627	scfh
heat in CO in ex. Gases	6,978,168	Btu/hr
heat in CO in ex. Gases	7.36	GJ/hr.

4.3.2 Emission Reduction

The CBMA report provides information on the composition of exhaust gases in a duct from the kiln to stack or chimney. Data reported by CBMA shows that:

1. The exhaust gases in the exhaust duct between the kiln and chimney are at 93.5 °C.
2. The gases including air leaks at the kiln top section, include pollutants - combustible gases such as CO (1.4%), particulates (192.2 kg/hr) and hydrocarbons (0.37%).
3. Oxygen concentration in exhaust gases is 15.14%.
4. Total volume flow of exhaust gases, including air leakage is 43,631 Nm^3/hr.
5. The combustible gases are at very low temperature and cannot react with oxygen presence in the gases or from air leaks.

The gas analysis taken in the duct between the kiln and chimney includes the effect of a large amount of air leaking into the kiln above the bed of raw meal or nodules charging. In order to evaluate the true conditions above the bed of raw material charged in the kiln, it is necessary to estimate temperature and gas analysis at the outlet or above the bed. This can be done by conducting an additional mass balance for O_2 in exhaust gases.

Table 14 shows an estimate of gas analysis (O_2 and CO) in the exhaust gases just above the bed and before the air is mixed. This analysis is based on the volume flow of air entering the kiln, available O_2 in the air and the amount of oxygen used in the combustion of coal. Note that this requires some trial and error to get a stable value of excess air to match mass balance. Based on this calculation, the O_2 concentration in the gases above the bed, before being mixed with leaking air, is estimated to be about 3.5%.

The measurements also indicate the presence of free CO and hydrocarbons in the exhaust gases leaving the chimney. With appropriate correction for air leaks, the measured value of CO (1.4%) will be actually 4.18% above the bed. The calculations are shown in Table 14. This clearly indicates that coal combustion in the middle section is incomplete and/or there is a chemical reaction between coal in raw meal nodules and CO_2 that is produced from combustion of coal in the middle or combustion zone. Temperature of the gases emerging from the bed is relatively low to burn CO even when the gases contain about 3.5% of oxygen.

Table 14. Estimate of Condition of Exhaust Gases Above the Raw Meal Bed in the VSK

Estimate of conditions above the nodule - raw meal bed in VSK			
cu.ft of exhaust gases (FG)	1.000		
cu.ft of air added	1.985	Trial and error method - Change cu.ft. of air added to match O2 concentration in Ex. Gas above the bed	
O2 concentration in Exhaust gases from the bed	3.5%	Calculated based on combustion of coal and available air	
O2 concentration in mix gases	15.14%	12.6% Measured by CBMA. This is corrected for presence of CO2 from calcination process	
Total gas volume	2.985		
O2 concentration in mix gases	15.14%	Calculated by use of excess air - trail and error. This should match number in	
Excess air used	199%	Calculated	
Temperature of ex. Gases - measured	93.50	Deg. C	Measured by CBMA
Ambient air temp	25.00	Deg. C	Measured by CBMA
Temp of gases above the bed before mixing cold air	229.47	Deg. C	Calculated

Table 15. Estimate of Heating Value for Combustible Gases Above the Raw Meal or Material Bed in the VSK.

Estimate of heating value - combustible gases in exhaust gases above the bed			
% CO in cooled ex. gases	1.40		Measured by CBMA
% CO in hot ex. gases	4.18		Corrected after accounting for air leakage above the bed
% HC in cooled exhaust gases	0.37		Measured by CBMA
% HC in hot exhaust gases	1.10		Corrected after accounting for air leakage above the bed
Heating value of HC	1,000.00	Btu/scf	Avg. value assumed
Heating value of CO	320.00	Btu/scf	Standard value
Heating value of combustibles (CO + HC) in ex. Gases	24.42	Btu/scf	Calculated
Heating value of combustibles (CO + HC) in ex. Gases	909.76	kJ/m^3	Conversion 1 Btu/scf = 37.259 kJ/m^3

Similar calculations, also shown in Table 15, for hydrocarbons indicate that the presence of 0.37% hydrocarbons in exhaust gases in the stack can be translated as 1.1% hydrocarbons in gases just above the raw meal (nodules) bed. Using standard heating value of CO (320 Btu/scf) and assumed heating value for hydrocarbons (1000 Btu/scf), estimated heating value of gases above the bed, before mixed with air leaks, is 24.42 Btu/scf or 909 kJ/m^3. The heating value of the hydrocarbons is expected to be higher than 1000 Btu/scf resulting in higher heating value for the gases.

The CBMA report states that exhaust gases from the kiln contain large amount (192.2 kg/hr) of particulates or dust that would include carbon from the nodules. If we assume that the coal content of dust is the same as the coal content of raw meal, (approximately 8% by weight), then it is expected that the dust may include about 15 kg of “coal” or carbon with total heat content of 0.416 GJ/hr. This gives additional heating value of 28.47 kJ/Nm^3 for exhaust gases above the bed. This is relatively small but can be used if necessary. Benefits of this heat are not considered in the following calculations since its availability is questionable.

Exhaust gases above the bed, as well as in the exhaust stack, may include several additional pollutants such as dioxin that were not monitored during this assessment. These are complex compounds of hydrogen and carbon with additional elements such as chlorine. They were monitored during earlier tests on this and other VSKs. The aforementioned analysis shows that:

1. The exhaust gases emerging from the bed are at about 230 °C.
2. The gases above the bed, before mixed with air leaks, contain 4.18% CO and 1.1% hydrocarbons and about 3.5% O_2.
3. Presence of CO and hydrocarbons indicates that there are other pollutants formed as a result of incomplete combustion of coal and the reaction of combustion products with coal at lower temperature. Past measurements have clearly indicated presence of several pollutants such PCDD/Fs, PCBs and HCB as unintentionally produced POPs from VSKs in China.
4. The combustible gases on the top of the bed are at a low temperature and cannot react with oxygen present in the gases or from air leaks.
5. Estimated heating value of gases above the bed, before mixing with cold air leaks, is about 900 kJ/Nm^3.
6. The combustible gases are diluted when they get mixed with air leaking from the doors etc. and heating value of the gas reduces to about 1/3rd or approximately 300 kJ/Nm^3.

4.4 Suggested Actions to Reduce Energy Use and Reduce Emission of Pollutants

The analysis discussed above indicates that the kiln gases leaving the bed contain about 15% of the total energy input to the kiln. These gases are causing major pollution problems for VSK users in China. As a solution to eliminate pollution problems and reduce energy use in VSKs, it is suggested that the upper section of the kiln be redesigned to reburn gases that cause pollution problems and recover energy that would be available from the modified kiln design.

Implementation of this suggestion requires that temperature of the gases to be raised to about 760 °C to 870 °C (1400 °F to1600 °F) by using additional heat and adequate residence time or space to complete combustion of the gases as well as the supplemental fuel used to supply additional heat. Heat of the clean gases from combustion of combustible gases generated in this section (or volume) could be recovered in a heat exchanger and used for heating combustion air for the added fuel as well as water that can be used in the process or other locations in the plant. Additional heat available can be used for heating of water or air used in other areas of the plant. A simplified schematic is shown in Table 13. Here the gases exiting the bed are heated by using a burner that preferably uses gaseous or liquid fuel. It may be possible to use coal but use of coal will required special burner design and considerations for combustion-related issues. A heat exchanger is used to recover heat for one or more uses mentioned above (Figure 15).

Calculations used to estimate additional heat requirements and possible heat recovery are shown in Table 16. It is assumed that the gas temperature would be raised in presence of oxygen to 870 °C (1600 °F) and sufficient residence time would be provided to complete combustion of gases containing CO_2 HC and other species containing H_2-C compounds.

The additional heat requirement is 6.6 GJ/hr, or about 10% of the current energy use. This additional heat will allow reburning of the combustible gases and generation of approximately 20 GJ/hr, almost 36% of the current energy use. This includes heat from CO and hydrocarbon combustion plus heat from fuel and preheated air used from the heat exchanger. It is possible to recover 60% to 70% of this heat and use it for preheating combustion air, water used in the process, and hot water or air used at other locations in the plant, if required.

Estimated recoverable heat, based on 60% heat recovery, is approximately 12.5 GJ/hr, or about 22% of the current energy use. The net effect would be a gain of approximately 6 GJ/hr energy saving and elimination of pollutants (Table 16). Implementation of this recommendation would require changes in the upper section of the kiln, installations of heating system for reburn, heat exchanger equipment and redesign of nodule feed system.

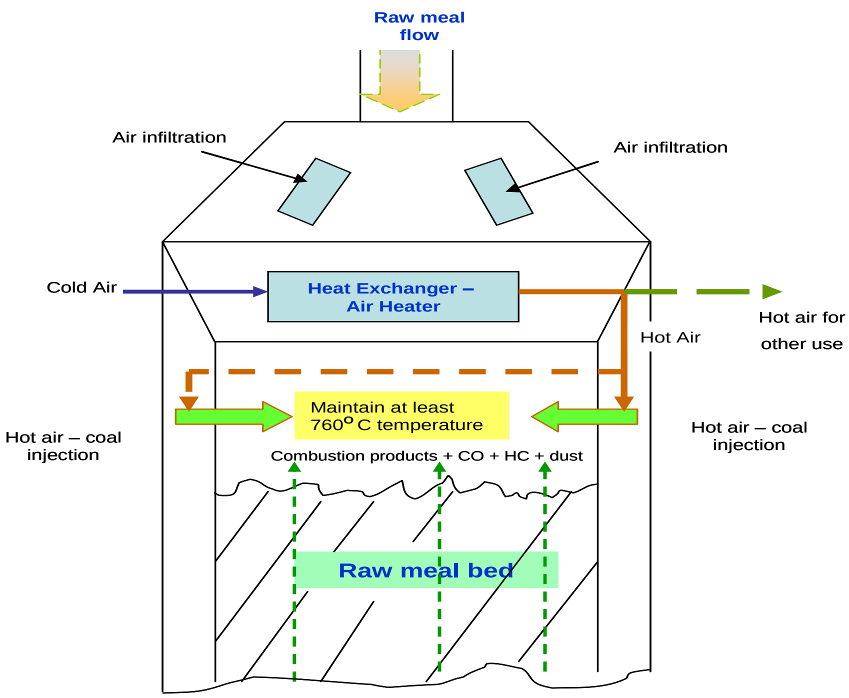


Figure 15. Schematic Illustration of Reburn and Heat Recovery System Arrangement for the VSK.

Table 16. Estimate of Recoverable Heat and Heat Requirement for the Proposed Reburn Scheme.

Estimate of Recoverable Heat and Heat Requirement for the Reburn Section		
Temp required for combustion of combustible gases	871.11	Deg.C
Temp of hot gases now	229.47	Deg.C
Temp difference for combustion of exhaust gases	641.64	Deg. C
Heat required for temp rise	23.10	Btu/scf
Av. Heat at 1600 F. stoich condition with use of hot comb. air	65%	
Heat required from "fuel" or unburned gases	35.54	Btu/scf
Heat from combustibles	24.42	Btu/scf
Heat required from additional fuel	11.12	Btu/scf
Additional fuel heat required for total volume of VSK bed ex. gases	6.22	MM Btu/hr
Additional fuel heat required for total volume of VSK bed ex. gases	**6.57**	**GJ/hr**
Sp. Heat of ex. Gases (CBMA data)	1.455	kJ/(m^3-C)
Volume of gases being heated (from the bed) plus air used for combustion of added fuel	16,379	Nm3/hr
Heat in exhaust gases	**20.8**	**GJ/hr**
Recoverable heat from these gases	60%	
Recoverable heat from these gases	**12.46**	**GJ/hr.**

5. Results of the Sino-US Cement Kiln Project

A *Workshop on Achievements of the Sino-US Cement Kiln Project and of Co-processing Technology on POPs Waste by Cement Kiln* was held on November 17, 2009 in Beijing, organized by Foreign Economy Cooperation Office of Ministry of Environmental Protection (FECO). In the workshop, the achievements of Sino-US Cement Kiln Project were introduced, while management and technical requirements of co-processing on POPs waste by cement kilns in China were also discussed. More than 70 people were invited to participate in this workshop including representatives and experts from related departments of Ministry of Environmental Protection, U.S. Environmental Protection Agency (EPA), China Cement Association, China Building Materials Academy, domestic and foreign cement production enterprises, and relevant scientific and research institutes.

According to monitoring results of pollutant emission and energy efficiency in the two evaluated cement plants, technical and process reform were implemented, while energy efficiency and pollutant emissions were evaluated. The evaluation results show that significant environmental and economic benefits were achieved after reforms. The achievements of the project presented in the workshop are as follows.
As one of the demonstrated enterprises, Shandong Shui Ni 1 Cement Plant reported their experience in the technical reform as follows:

1). Reducing energy consumption during cement kiln production process by sufficient use of kiln head, tail, and body's waste heat in generation and raw material drying;
2). Efficiently decreasing heat loss throughout cooling system by applying advanced cooling devices;
3). Reducing coal consumption meanwhile increasing clinker output and quality by utilizing high-efficiency combustion devices to rationally apportion air and coal which guarantee complete combustion of coal;
4). Decreasing heat loss throughout the surface of kiln system by choosing high performance refractory and heat preservable material;
5). Introducing online automatic control and analysis system to ensure continuously stable operation.

Compared to the situation prior to the implementation of the suggested reform measures in the Shui Ni 1 Cement Plant, the following was observed after the reform: emission concentration of PCDD/Fs fell by 91.8%, polychlorinated biphenyls (PCBs) fell by 98.5%, and hexachlorobenzene (HCB) fell by 57.5%. There still existing a large number of mechanical vertical shaft kiln production lines in China, if technical reforms can be implemented to some of the under-developed production lines and rotary kiln production lines can be improved, it will be helpful to emission reduction in POPs from cement industry. Key factors affecting POPs emissions from cement kilns include: incomplete combustion, POPs in raw materials, organic compounds in raw materials becoming precursory compounds, chlorine in raw materials, catalytic metals existence, impact of operating conditions including stability of operating conditions, and the cooling rate of the flue gas.
In the Shui Ni 1 Cement Plant, through energy efficiency analysis of kiln #2 (installed as part of technical reform) vs. the older kiln #1 (the evaluated kiln) the following quantitative results were reported:

1) Thermal efficiency improved by 6.1%;
2) Kiln #2 applied the type of coolers with the latest technology of control-flow, which can efficiently reduce heat consumption of clinker burning by efficiently reclaiming heat from clinker out of kiln and by improving the temperature of secondary air and tertiary air;
3) Volume of waste gas out of pre-heater declined and the temperature of waste gas lowered.
4) Thermal efficiency of kiln systems increased by 6.1%;
5) Annual raw coal consumption dropped by 5232 tons, a coal saving rate of 2.13%.
6) Carbon dioxide emissions for the whole year fell by 15329.8 tons of CO_2, a reduction rate of 2%.

Through energy efficiency analysis, after and before the technical reform of the vertical shaft kiln production line in Shui Ni 2 Cement Plant, the following quantitative results are achieved:

1) Thermal efficiency of the kiln increased from 53.53% to 55.19%, mainly due to a decline in heat consumption of clinker burning;
2) Incomplete combustion decreased. The concentration of carbon monoxide in waste gas from kiln tail dropped from 1.4% to 1.0%;
3) Heat loss throughout the surface of kiln system declined, mainly because of heat preservable layers on the surface and in various pipelines;
4) Volume of waste gas decreased.
5) Thermal efficiency of kiln systems increased by 1.66%;
6) Annual raw coal consumption dropped by 542 tons, a coal saving rate of 2.69%.
7) Carbon dioxide emissions for the whole year fell by 1587.95 tons of CO_2, a reduction rate of 2.69%.

Compared to the situation prior to the implementation of the suggested reform measures in Shui Ni 2 Cement Plant, the following was reported: PCDD/Fs fell by 97.4%, PCBs fell by 96.1%, and HCB fell by 76.1%.

6. Conclusions

The assessment included detail analysis for major areas of energy use or loss in the clinker production system that uses a NSP rotary kiln or vertical shaft kiln in a cement plant. Based on analysis of the data collected during this assessment, several actions are suggested that could lead to reduction in coal use and reduction in emission of gaseous pollutants from the system.

Specific actions suggested for NSP rotary kiln at Shui Ni 1 Cement Plant are: 1. reduce excess air use in coal burners, 2. reduce air leakage in the system through control of pressure and/or eliminating openings or gaps through which air leaks into the system, and 3. use of improved insulation and refractory in the kiln. These measures, if fully implemented, would reduce net (actual use minus equivalent of power production) coal consumption from 119 kg/ton kg of clinker to 103 kg/ton of clinker or a reduction of 16 kg coal per ton of clinker production – a reduction of 13.4%. Using a coal cost of 400 RMB/ton of coal, 360 days/year operation, and 5000 tons/day (approximately 208 tons/hour) clinker production rate, potential savings would be 11.52 million RMB/year.

Specific actions suggested for VSK at Shui Ni 2 Cement Plant are: 1. Preheat nodules by using hot water and/or using waste heat. 2. Pre dry nodules using waste heat from exhaust gases or air used for cooling nodules. 3. Reburn CO-combustible gases and recover heat for use in the process or plant. 4. Reduce areas of air leaks to increase temperature of exhaust gas and use a heat exchanger to recover heat by recovering heat for nodule making process. 5. Control kiln pressure to avoid negative pressure at the clinker discharge level.

According to monitoring results of pollutant emission and energy efficiency in demonstrated enterprises, technical and process reform were implemented, while energy efficiency and pollutant emission were evaluated. The evaluation results showed that significant environmental and economic benefits were achieved after reforms.

Acknowledgements

This work was supported by the U.S. Environmental Protection Agency, Office of International Affairs through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We would like to thank Dr. Suzanne Giannini-Spohn of the U.S. EPA for her valuable support and guidance throughout this project. We would also like to thank Ding Qiong and Hu Jian of China’s Ministry of Environmental Protection for their support during this project.

We would also like to thank the staff of the China Building Materials Academy and the China Building Material Test & Certification Center who assisted us with the on-site measurements and monitoring information. We would also like to thank the staff at both the Shui Ni 1 and Shui Ni 2 cement plants in Shangdong Province of China for their helpful assistance and warm hospitality during our visits.

References

Ash Grove Cement, n.d., "Cement Manufacturing Process," http://www.ashgrove.com/careers/pdf/manufacturing.pdf

Cembureau, 1997. *Alternative Fuels in Cement Manufacture: Technical and Environmental Review.* Brussels: Cembureau.

http://www.cembureau.be/Documents/Publications/Alternative_Fuels_in_Cement_Manufacture_CEMBUREAU_Brochure_EN.pdf

China Building Materials Academy (CBMA), 2007a. *Energy Assessment Report – Shui Ni 1 Cement Plant.* Beijing: CBMA.

China Building Materials Academy (CBMA), 2007b. *Energy Assessment Report – Shui Ni 2 Cement Plant.* Beijing: CBMA.

Gabbard, W.D. and Gossman, D., 1990. "Hazardous Waste Fuels and the Cement Kilns," *ASTM Standardization News*. http://gcisolutions.com/HWF&CKS.htm

United Nations Environment Programme (UNEP), 2001. *Standardized Toolkit for Identification and Quantification of Dioxin and Furan Releases.* Geneva: UNEP Chemicals.

United Nations Environment Programme (UNEP), 2008. *Stockholm Convention on Persistent Organic Pollutants (POPs).* http://chm.pops.int/default.aspx

United States Geological Survey (USGS), 2009. *Mineral Commodity Summaries: Cement*. http://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2009-cemen.pdf

World Business Council on Sustainable Development, 2004. *Formation and Release of POPs in the Cement Industry.* Foundation for Industrial and Scientific Research of Norway. http://www.wbcsd.ch/web/projects/cement/pop-report.pdf